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Electrolysis of Titanium in Heavy Water

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THESIS APPROVAL

The abstract and thesis of Radovan Kopecek for the Master of Science in Physics were presented June 29, 1995 and accepted by the thesis committee and the department.

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ABSTRACT

An abstract of the thesis of Radovan Kopecek for the Master of Science in Physics presented June 29, 1995.

Title: Electrolysis of Titanium in Heavy Water

The purpose of these studies was to determine if results similar to those of Fleischmann and Pons could be obtained using a titanium cathode instead of palladium in an electrolysis in a heavy water cell. The electrolyte consists of D_2O and H_2SO_4. Two experiments have been performed to examine the features of this electrolysis. As titanium shows the same properties to attract hydrogen, it seemed possible that excess heat could be produced. Radiation was monitored, and the surface of the titanium cathode was examined

before and after electrolysis for any changes in the morphology and composition, hoping to discover new elements that can be created only by fusion reactions in the cell, i.e. by transmutation. The heat and radiation effects have been evaluated in comparison to a control cell, using the same electrolyte and current. The only difference was the cathode, which was of platinum.

It appears that excess heat is produced during electrolyses of heavy water with a titanium cathode. The amount of this excess heat was 750 cal in a one hour period, an energy gain of 44%. No significant emission of any of the products associated with a "classical" deuterium-deuterium fusion was observed during either experiment, i.e. heat but no radiation. Unexpected elements were found in both experiments, i.e. K. Cr, Fe, Ni and Zn. Remarkable is the fact that the new elements always occur very close in the periodic table to an impurity element, i.e. Cu and Zn.

ELECTROLYSIS OF TITANIUM IN HEAVY WATER

by

RADOVAN KOPECEK

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
in
PHYSICS

Portland State University
1995

ACKNOWLEDGMENTS

My first and very special thanks go to John Dash who was extremely supportive during my studies at Portland State University. I would like to thank him for his patience and his trust in letting me use his equipment especially the SEM. I am also very grateful to Franzi and Ken Herman who helped me get settled in Portland and made my stay more colorful. Many thanks to my fellow students Christoph Zaczek, Silvie Miguet and Grant Noble for very helpful discussions. I also would like to express my gratitude to my Kappenspiel-buddies: Gabi, Cokerpeli, Volker, Steffen and Alex. Děkuji také velice moji rodině, která mě celou dobu moc podporovala. At the end my very, very special thanks should go to my kicsi Moncsi with her little Schiefmund.

This thesis is dedicated to Ali and Oli.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

TABLE PAGE

INTRODUCTION

A lot of effort and money have been invested into research to enable fusion-reactions at low temperatures. Steven Jones had been pursuing the goal of cold fusion since the early 1980's. Working for a number of years on muon- catalyzed fusion, Jones had then begun to look into the possibility of beefing up nuclear fusion through the use of extremely high pressures.

But two other scientists (chemists rather than physicists) had suddenly moved into the scene and appeared to have changed the whole cold fusion story. Martin Fleischmann and Stanley Pons, using a small electrolysis cell with a palladium cathode and heavy water electrolyte, observed a large amount of heat produced by the cell. The project was worked out in the Pons family kitchen. In fact, the first experiments were fairly simple and done just for fun. To save money, Pons was employing his son Joey, who had recently graduated from high school, as an assistant. In these early experiments nothing spectacular happened and the whole thing seemed to be going nowhere. Then, one night in 1989, the cell they were using grew so hot that it melted down. At that moment, Pons realized, the cell must be producing an enormous amount of energy. On that day, cold fusion became a reality, at least to Fleischmann and Pons.

To understand the construction of Fleischmann and Pons cell, one must begin with that curious rare metal, palladium. This gray-white element has been around scientists' laboratory for almost 200 years and is used in a variety of electrical experiments and as a chemical catalyst. The most interesting property of palladium is its ability to absorb hydrogen. This property of hydrogen absorption has been known for a long time. In fact, scientists used palladium to store hydrogen isotopes. As the hydrogen atoms enter the palladium, they give up their electron to move around with the other electrons in the metal itself. The hydrogen nuclei then begin to pack together. But would this "passive" packing bring the nuclei that close together to produce fusion? The business of pumping hydrogen gas into palladium had been going on for quite some time and yet no one had spoken about nuclear fusion. What was needed was some additional force to set the deuterium nuclei even closer together. Pons and Fleischmann speculated that the most practical way of forcing hydrogen atoms into palladium metal would be to use an electrolytic cell.

In fact, their cell is a simple variant on an experiment that is performed in many school chemistry departments:

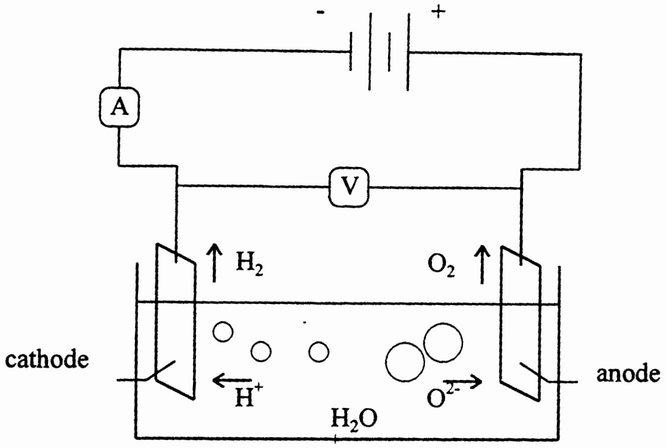


Figure 1. Electrolysis of light water performed in many lectures.

Water can be split into its base components by electrolysis. An ionic current is passed from one electrode to the other through the water itself. Hydrogen atoms transfer their electrons to oxygen, which becomes negatively charged. Each positively charged hydrogen nucleus is attracted toward the negative electrode. Once it reaches and sticks to the surface of the electrode, it is able to attract an electron and turn back into a neutral hydrogen atom, then into a hydrogen molecule, which bubbles off as hydrogen gas.

Fleischmann and Pons were attempting a variation on this basic experiment. They passed a current through heavy water so that, instead of the deuterium gas bubbling off at the negative electrode, the individual atoms would be driven into the metal itself. Pushing up the voltage on the cell itself increased the "electrical pressure" on the deuterium nuclei and crowded them even more tightly into the electrode.

There are several characteristic "signatures" that indicate a nuclear reaction is going on. They were attempting to detect all of them, but for Fleischmann and Pons the most convincing argument was the heat being released. The degree of heat in the palladium electrode suggested a release of energy that was far higher than anything achievable in any chemical reaction. The problem with this was that the large amount of heat being generated in the cell should be accompanied by a huge radiation. There was plenty of heat but not enough nuclear radiation.

Later, two chemists at the University of Utah were to develop a theory to explain this process. They suggested that a form of nuclear fusion was occurring in which the energy released is given directly to the metal so that no nuclear radiation or neutrons are produced. In short they claimed that a totally clean form of nuclear energy was theoretically possible ($D + D \rightarrow {}^4He$ + Energy). M. Miles was recently performing many experiments to examine this matter 6). For experiments producing excess power, the measured ^4He concentration was higher than the background level. If this is the only reaction that governs the process, then everything would be simple. There would be pure heat and no radiation. But the Utah group estimated that one in every 10 millions fusions would still go along the conventional path (e.g. $D + D \rightarrow {}^3He + n +$ Energy) and that means some nuclear radiation. Fleischmann and Pons claimed to detect neutrons and gamma rays during their experiments. Later, some scientific groups confirmed 5) some of their findings, others were to criticize 10) the way the measurements had been carried out and deny the detection of nuclear radiation.

At the present time a large number of experiments is going on to get clearer results in this field. The leading countries in this research are Russia, Japan, Italy and the USA. Various theories have been presented to explain the process, which can not be simply understood by quantum mechanics 8). This is the main reason why most physicists do not want to deal with this matter.

In the experiments reported here - electrolysis of titanium in heavy water- the aim was to produce results similar to those of Fleischmann and Pons using a titanium cathode. As titanium shows the same properties to attract hydrogen, excess heat should be produced. The other purposes of these studies were to monitor radiation and mainly to examine the titanium before and after electrolysis for any changes in the structure, hoping to discover new elements that can be only created by fusion reactions in the cell, i.e. by transmutation.

The heat and radiation effects have been evaluated in comparison to a control cell, using the same current. This cell differs just slightly from the experimental cell. There are two possibilities to run this experiment:

1) Experimental and control cell both have a platinum anode and a titanium cathode. The only difference is the electrolyte. $D_2O + H_2SO_4$ is used in the experimental cell, $H_2O + H_2SO_4$ in the control.

2) The electrolyte is in both cells the same as above for the experimental. The difference in this kind of experiment is the cathode consisting of titanium in the experimental, platinum in the control. The anodes still consist of platinum.

In both cases, excess heat and radiation should be detected in the experimental cell. The second possibility has been chosen for the two following experiments.

DESCRIPTION OF THE EXPERIMENTS

Two experiments have been performed, using an experimental cell (D cell) with platinum anode and titanium cathode and a control cell (C cell) with only platinum for both electrodes. The electrolyte used in both cells was $D_2O + H_2SO_4$. The concentration of the acid in the electrolyte in the second experiment differs from the first one, for some reasons explained later. The sulfuric acid has the purpose to ionize in the heavy water. This makes it possible to use a lower cell voltage.

For the collection of the temperature data, copper-constantan thermocouples were used on the outside of both cells. For possible neutron and gamma ray detection, thermoluminescent dosimeters (TLDs) from the Radiation Detection Company were used along with two Geiger-Mueller counters (Pasco Scientific, Model: SE 7985). For the TLDs a combination of ^{6}LiF and ^{7}LiF chips has been used. The technical data for these devices can be found in the appendix. A constant current source was used and cell voltages were monitored. The titanium cathode before and after the experiment was examined by SEM (scanning electron microscope). All micrographs and EDS (energy dispersive spectrometer) spectra were taken using an ISI-SS40 SEM equipped with LINK AN10000 EDS.

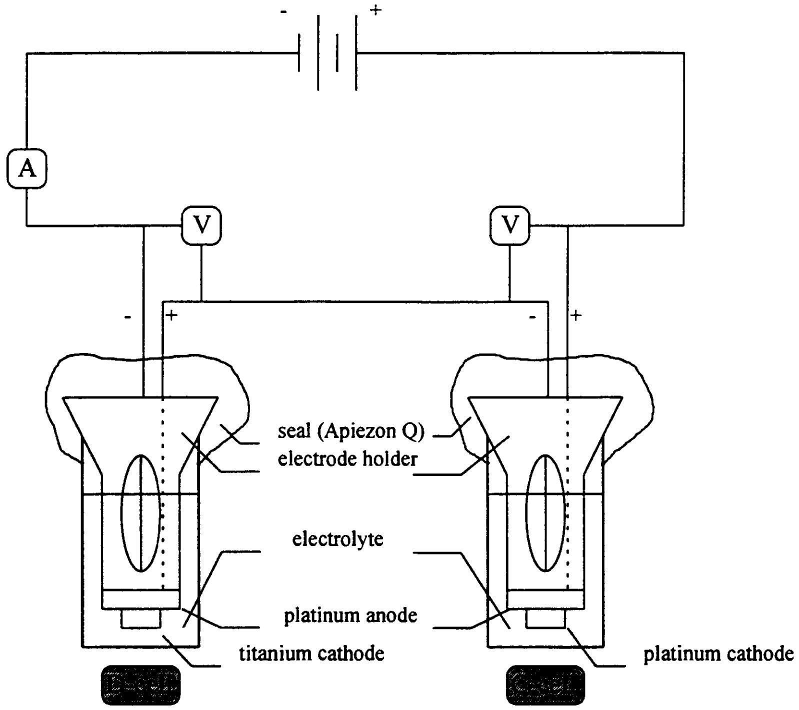


Figure 2. Schematic diagram showing components of electrolytic cells and circuit of experimental (D) and control (C) cell.

FIRST EXPERIMENT

The cells consist of small glass cylinders (about 25 ml volume) and Teflon electrode holders. The electrolyte contains heavy water with 0.06 mol fraction sulfuric acid. 99.99+% pure titanium from Johnson Matthey Company was used as a cathode in the experimental cell (stock number: 13975, lot number: G07D10). The chemical analysis determination of impurities can be found in the appendix. The cathode in the control and the anodes in both cells were made from Johnson Matthey 99.9% pure (stock# 00261, lot# B24E24) platinum foil of 0.30 mm thickness. The areas of both cathodes have been calculated to get a current density of 2 A/cm^2 by a given current of 0.75 A. Because of the small thickness of the titanium foil (0.25 mm), the surface area of the edges was neglected in the calculations. Using Teflon tape, the rest of the cathode area was covered to isolate it from electrolysis. A recombination catalyst (20% Pt on Carbon from Protech Company) was used in both cells to avoid a significant loss of electrolyte and to keep it at a stable pH. For the same reason both cells were sealed with Apiezon Q (James G. Biddle Company). The exact data of this seal are unknown (compounds, specific heat) but its used only at the outside of the cells.

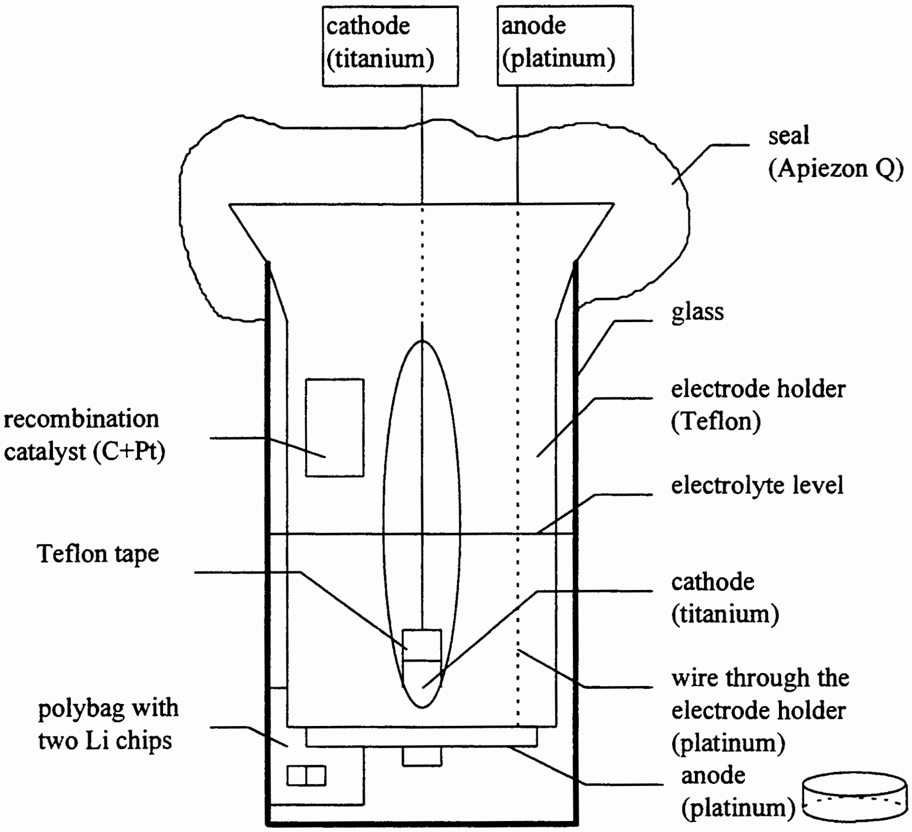


Figure 3. Electrolytic cell (D cell) with a platinum anode and a titanium cathode. C cell has a platinum cathode.

The electrolytic cells were connected in series (Figure 2.) and a constant current source supplied them with 0.75 A. The cell voltages have been recorded by a strip chart recorder. The first experiment was expected to run for more than two days, but after 21 hours and 47 minutes the concentration of the sulfuric acid in the electrolyte became so high that it reacted strongly with the Ti cathode and the cathode broke in two halves at the connection with the Teflon tape. The total loss of electrolyte in both cells was the same, about 2.5 ml. At the beginning each cell contained 9 ml. This loss caused a decrease in the pH of 0.5. Therefore the concentration of the acid had to be lowered in the next experiment to make it run for a longer time.

Radiation

Each cell contained two LiF chips (Li-6 and Li-7) sealed in a polybag to protect them from the electrolyte. The background was taken by an additional pair outside of the cells. Li-6 is sensitive to betas, x-rays, gammas and neutrons while Li-7 is sensitive to all except neutrons. Using this feature allows design of a dosimeter which can detect neutron doses by subtraction of Li-7 readings from Li-6 readings. The chips were returned to the supplier for analysis after each experiment.

To understand the physical process of thermoluminescence in these chips, a simple model can be considered. A primary stimulation event (alpha, beta, gamma or neutron for Li-6) excites an electron out of the valence band of the solid, producing a hole in the valence band and a electron in the conduction band, as shown in Figure 4.12)

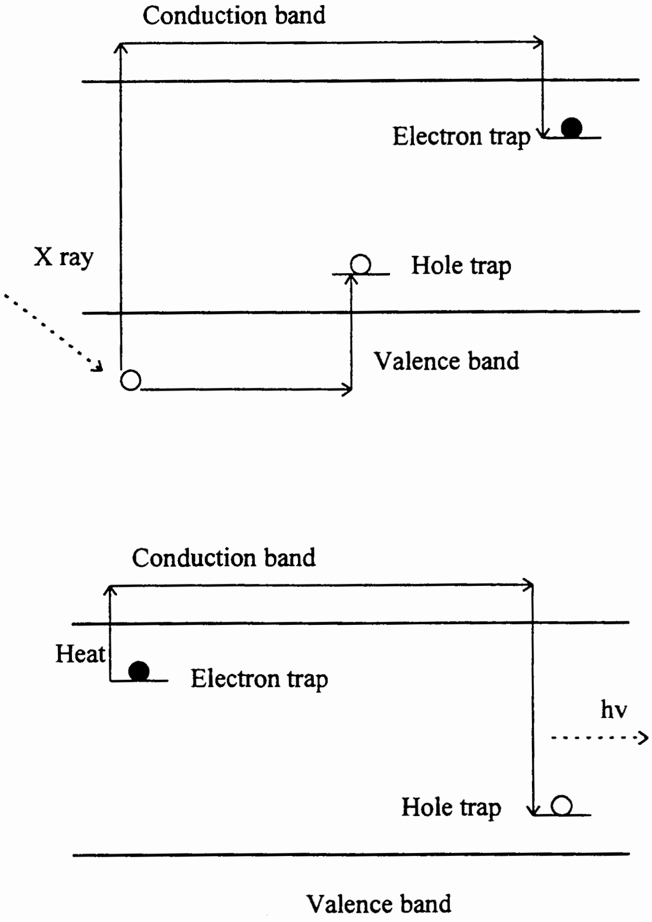


Figure 4. Simple schematic band model for TL (trapping and detrapping).

Both electron and hole wander in their respective bands until they each find a localized defect where they become trapped. Additional energy is required for either the electron or a hole to be detrapped. This can be done, as shown in Figure 4 , by heating. The free electron then wanders in the conduction band until it is able to recombine with a hole. Light is given off during the recombination process. This light is the thermoluminescence (TL), which may be recorded as a function of temperature.

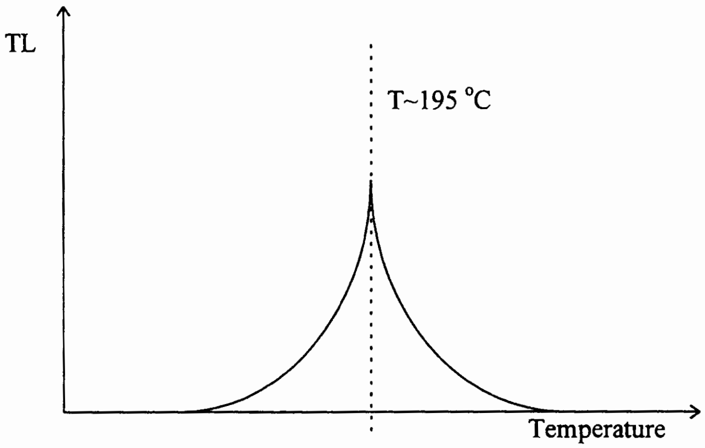


Figure 5. TL glow peak for ^{6}LiF and ^{7}LiF.

The maximum intensity for both Li chips occurs at a temperature of 195 °C (Appendix). This property is good for the experiments, where the expected heat in the cells is about 70 °C maximum. This means that the electrons will not get detrapped during the experiment itself. The specifics of the trapping and recombination processes can be complex, depending on the amount of retrapping occurring at the original trap, the presence of other traps, and nonluminescent recombination paths. The second important feature for these experiments is that the both chips have identical tissue-equivalent response to photons but very different response to both thermal and fast neutrons (thermal: eV range, fast: MeV range) 4).

The results from the Radiation Detection Company for experiment one are given in Table 1.

set	TLD	Light Output	^{137}Cs eq mrem
Bkgd	600	10	8
	700	13	8
C	600	11	8
	700	0	0
D	600	0	0
	700	0	0

Table 1. Readings obtained from the LiF chips.

There have been no significant readings out of the chips. Net doses under 10 mrem Cs equivalent are not statistically significant. For this reason longer experiments are desirable. Next time also Geiger-Mueller counters will be used to measure possible gamma rays and other radiation.

What seems very strange is that the counts for the ^{7}LiF chips for both cells and ^{6}LiF for the D cell are even under the background. This is because the cells were surrounded by lead bricks, and the background radiation could not reach them. This was improved in the second experiment.

Temperature

Each component in the D cell was slightly heavier than its counterpart in the C cell in order to exclude mistakes on heat output from the two cells. The temperature during this experiment was determined with only one thermocouple on the outside of each cell and recorded by a strip chart recorder. Because of the very unstable voltage (bubbles at the cathode) in each cell it was impossible to calculate the power input into the cells. This makes temperature calculations senseless. For the next experiment six thermocouples were used for each cell and the voltage was stabilized.

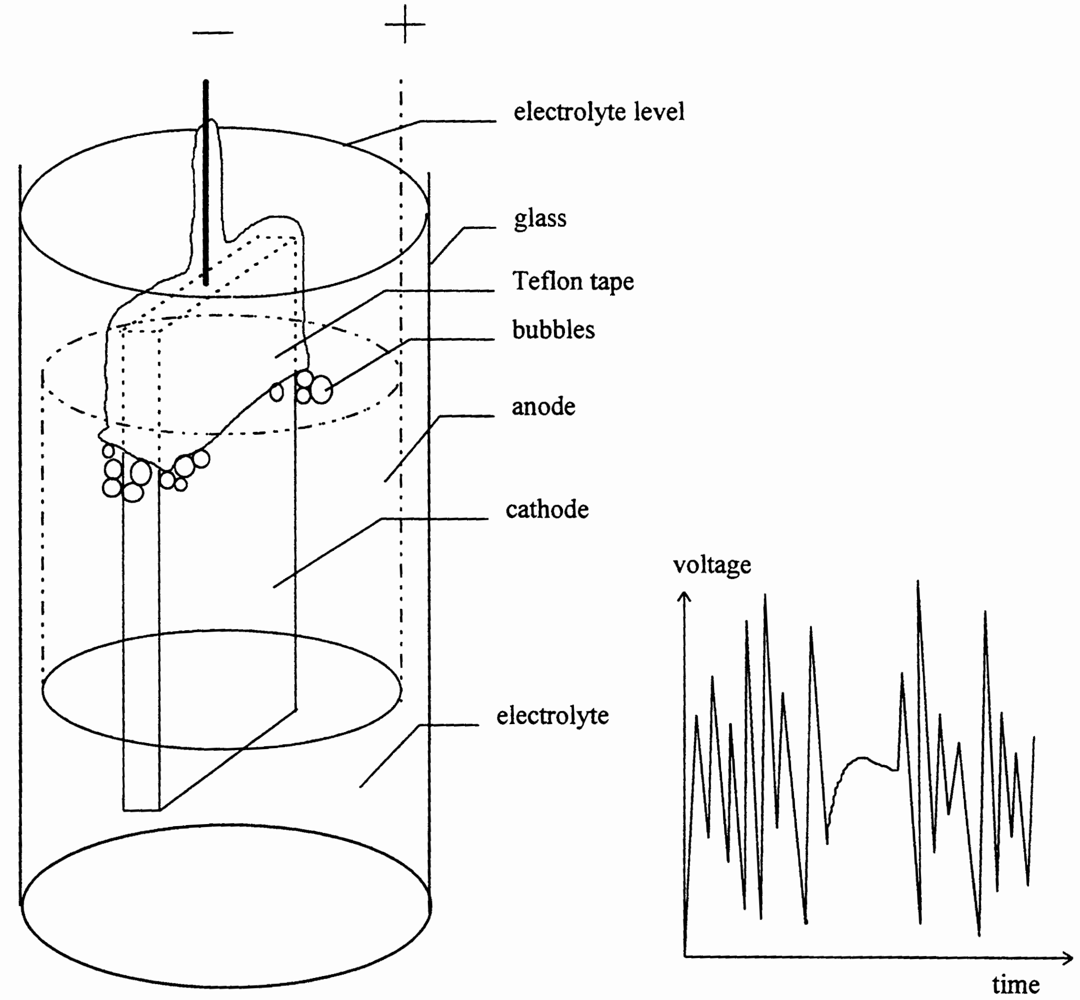


Figure 6. Geometry of bubble formation and the resulting instable voltage.

The accumulation of the bubbles was due to the Teflon coverage. Therefore the resistance between the cathode and the anode changed drastically with time, depending on the amount of bubbles surrounding the titanium cathode.

As is well known, the resistance of any conductor is proportional directly to its length and inversely to its cross-sectional area, namely,

$$R = \rho \frac{l}{A}$$

where R is the resistance in ohms, l the length in centimeters, and A the area in square centimeters (1). The proportionally constant ρ, termed the specific resistance, is the resistance of a conductor 1 cm in length and width a cross-sectional area of 1 cm^2. The value of ρ depends on and is characteristic of the nature of the conductor. The conductance L is the reciprocal value of R:

$$L = \frac{1}{R} = \frac{1}{\rho}\left(\frac{A}{l}\right) = L_s\left(\frac{A}{l}\right)$$

L_s is the specific conductance of the conductor. Of greater significance is the equivalent conductance Λ which is defined as follows

$$\Lambda = 1000\ L_s/C$$

where C is the concentration of a solution in gram equivalents per liter(1). The equivalent conductance Λ also varies with temperature (2). For most pure liquid electrolytes, the experimental log Λ versus 1/T plots are essentially linear.

This implies the usual exponential dependence of a transport property upon temperature

$$\Lambda = \Lambda_0 \exp(-E_\Lambda/RT)$$

where E_Λ is the activation energy and R the Avogadro-constant. Out of these equations the resistance is proportional to

$$R \sim \{\exp(1/T)\}\{l/A\}$$

Out of this, the unstable voltage is explainable. During bubble formation the reduction in area of the cathode increases the resistance and therefore the voltage increases. When a bubble disappears the resistance drops rapidly. The temperature dependence can be observed in the second experiment. As the temperature in the cell increases, the resistance gets lower, and the voltage drops slowly. This can be observed in Figure 25.

Morphology and microanalyses of the Ti cathode

The cathode was ultrasonically cleaned in deionized water bath several times, each for five minutes. The same procedure was done with the specimen holder (Al). Then the electrode was attached to the SEM specimen holder with conducive tape. The thin window of the EDS detector was in place, thus allowing detection of atomic number six and above. The sample was tilted 45 degrees along its longitudinal axis for efficient X-ray detection of the surface relief.

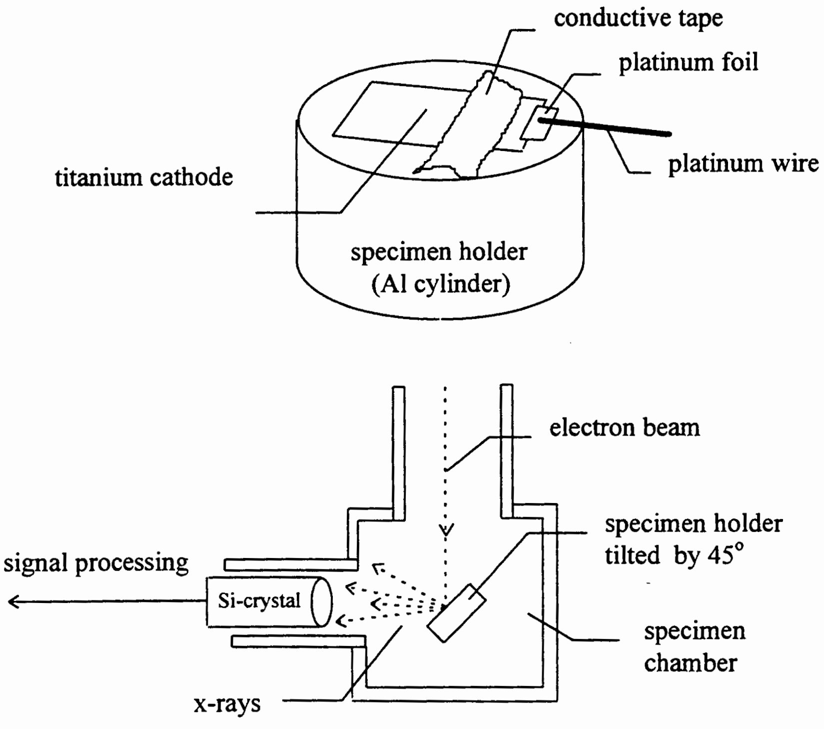


Figure 7. Specimen holder with a titanium cathode and geometry of the energy dispersive spectrometry (EDS).

Analysis before electrolysis:

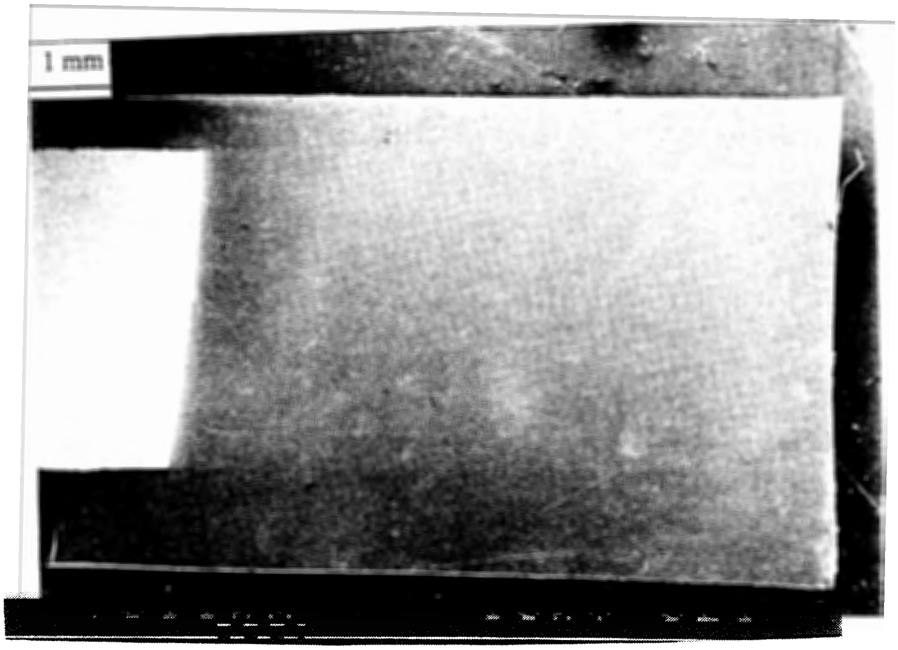


Figure 8. Titanium cathode before electrolysis.
(working distance 45 mm, no tilt, magnification 11x)

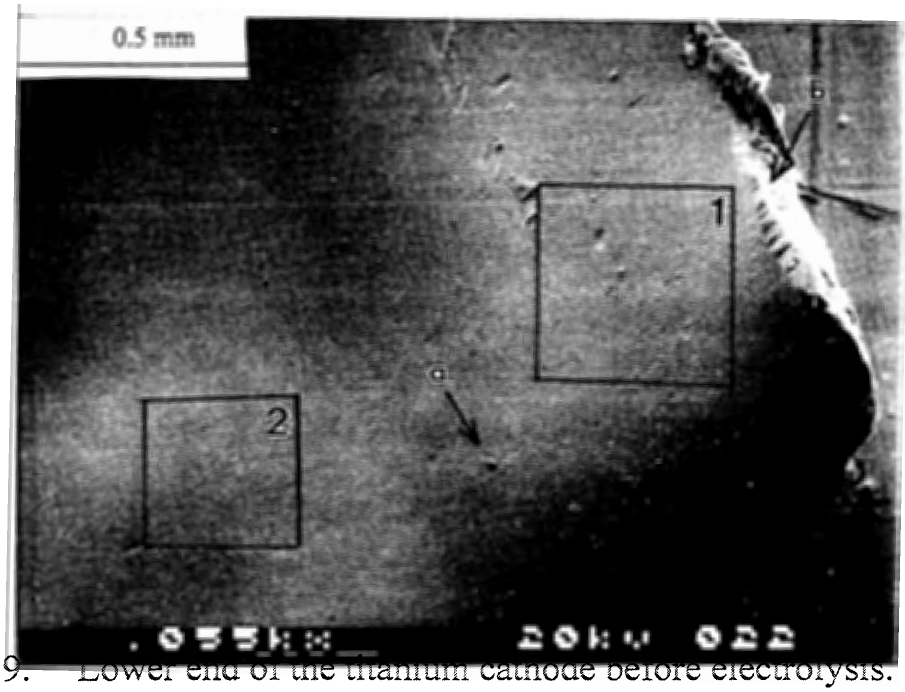


Figure 9. Lower end of the titanium cathode before electrolysis.
(working distance 10 mm, tilt 45°, magnification 55x)

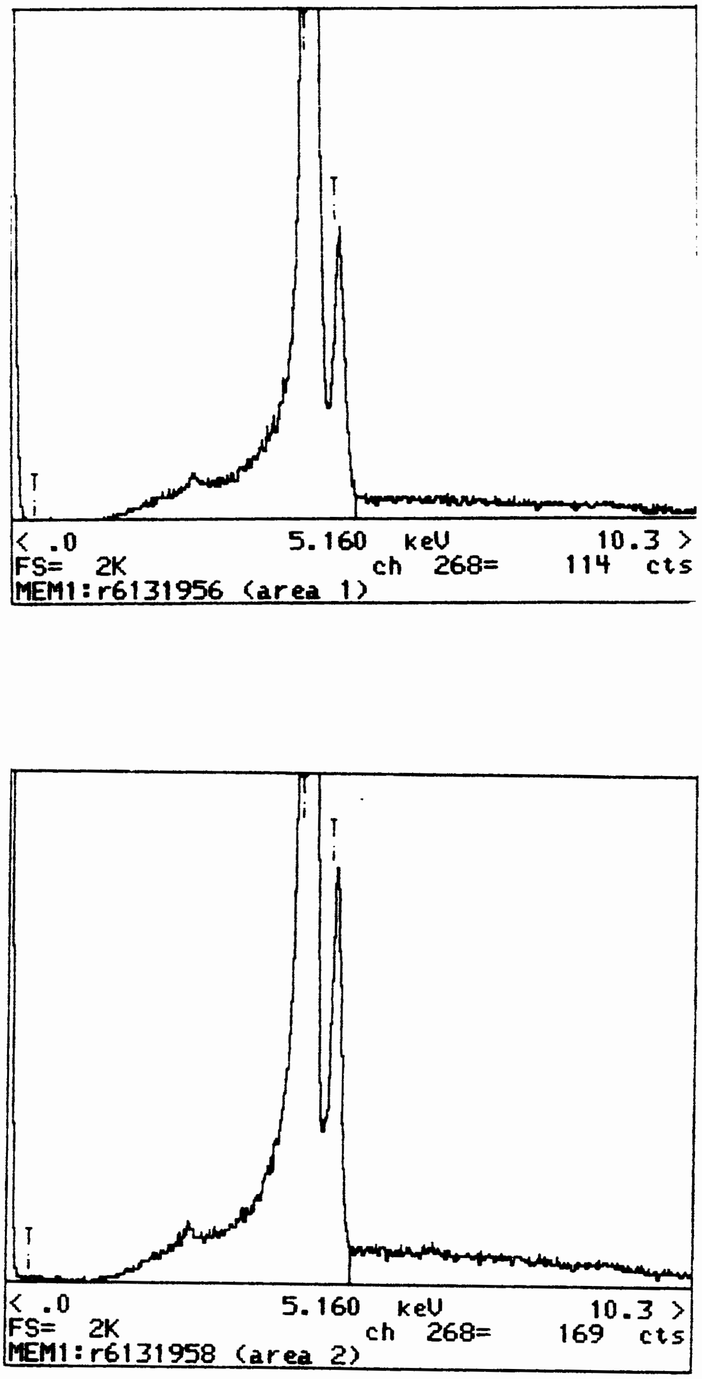


Figure 10. EDS spectra of areas marked in Figure 9.

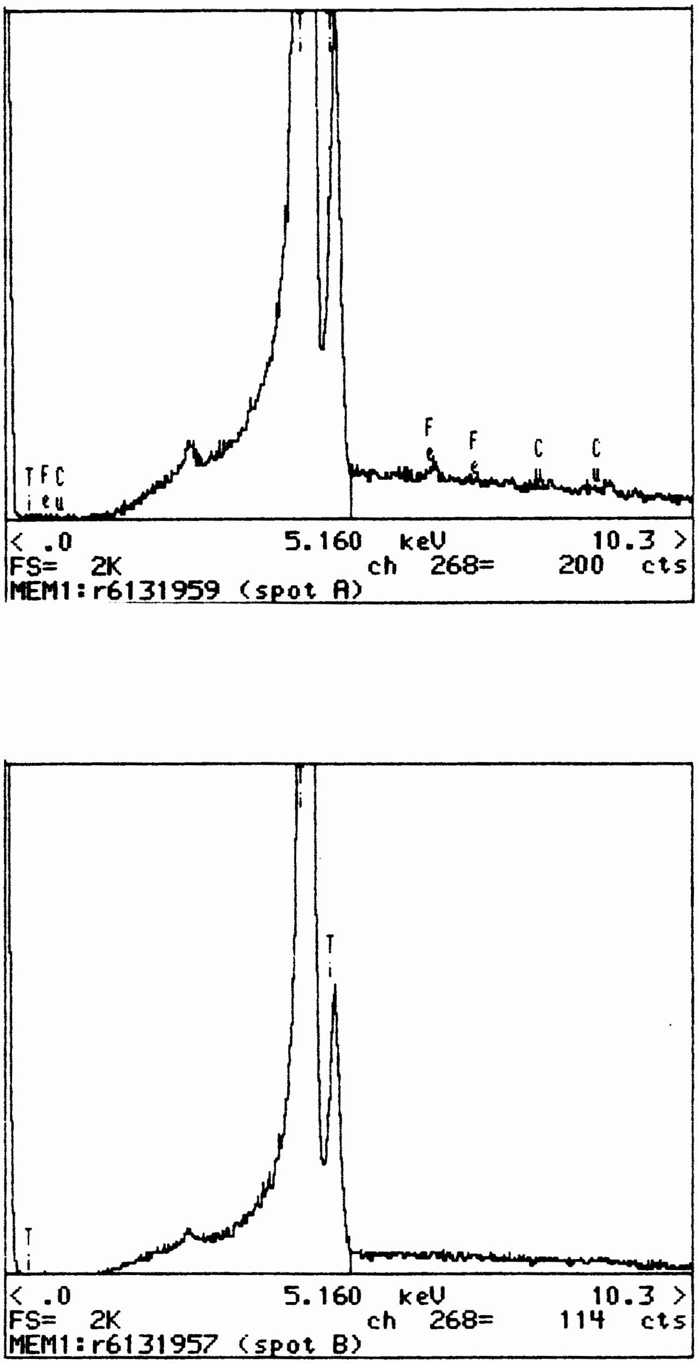


Figure 11. EDS spectra of spots marked in Figure 9.

From the spectra it can be seen that there is no significant impurity on the cathode. Titanium is the only element to be detected (compare also the certificate of analyses from Johnson and Matthey Catalog Company in the appendix) with small Fe and Cu peaks. During the whole examination of the titanium cathode before electrolysis similar spectra were detected. Fe is the largest impurity (6.60 ppm), Cu has a possible source from spot welding. Although the thin window was in place no C or O was detectable. It is possible that is was frozen during the examinations.

The three most prominent peaks that can be seen on the spectra is the K_α line at 4.510 keV and the K_β at 4.931 keV of titanium and a Si escape peak due to the Si detector. This is the Ti K_α line shifted by the Si energy of 1.740 keV 14), i.e. at 2.770 keV.

Analyses after electrolysis for 22 hours:

After the electrolysis the cathode was so thin that it was impossible to clean it ultrasonically without destroying it. The only cleaning possible was to wash it gently several times in deionized water. The cleaned electrode was again placed on a SEM electrode holder, this time just covered with aluminum foil taped to the stub to avoid any damage.

Possible elements on the cathode due to deposition from cell components or from the electrolyte:

- Pt (anodes and recombination catalyst)
- Cu (due to spot welding)
- C (recombination catalyst)
- Fe (the strongest detectable impurity of the Ti cathode (6.6 ppm))
- Al (glass)
- Ca (glass)

Al and Cu characteristic x-rays might also arise from the stub to which the Ti cathode was attached in the SEM.

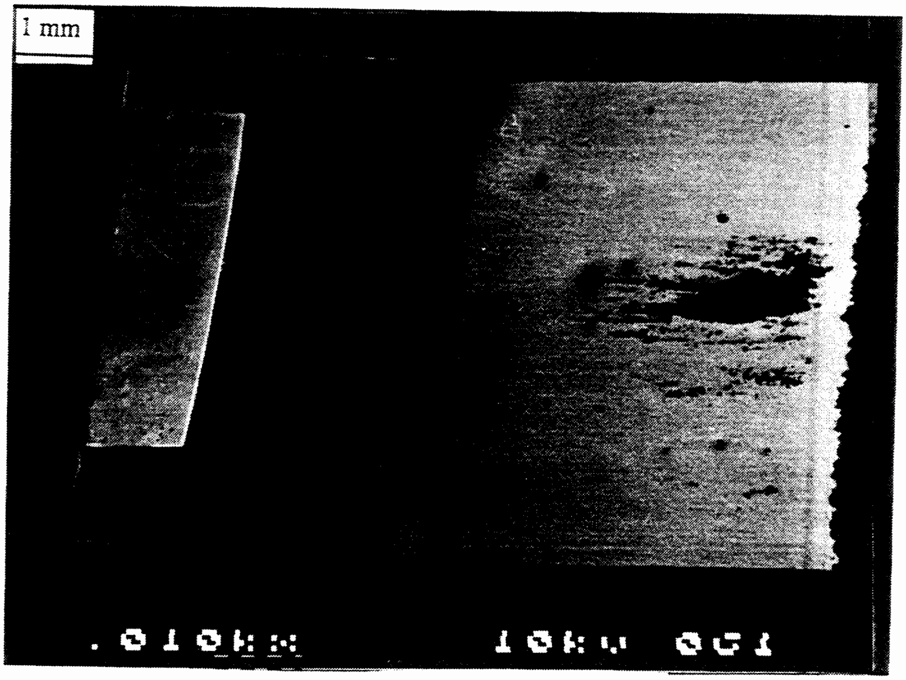


Figure 12. Titanium cathode after electrolysis. (same area as in Figure 8)

The right part of the cathode is the part that has been uncovered during the electrolysis. It was attacked by the acid at temperatures above room temperature and became transparent. (An additional experiment has been performed with a piece of Ti in the same electrolyte by temperature of 50 °C. Even without electrolysis the titanium became transparent). The covered part stayed almost the same as can be seen in Figure 12.

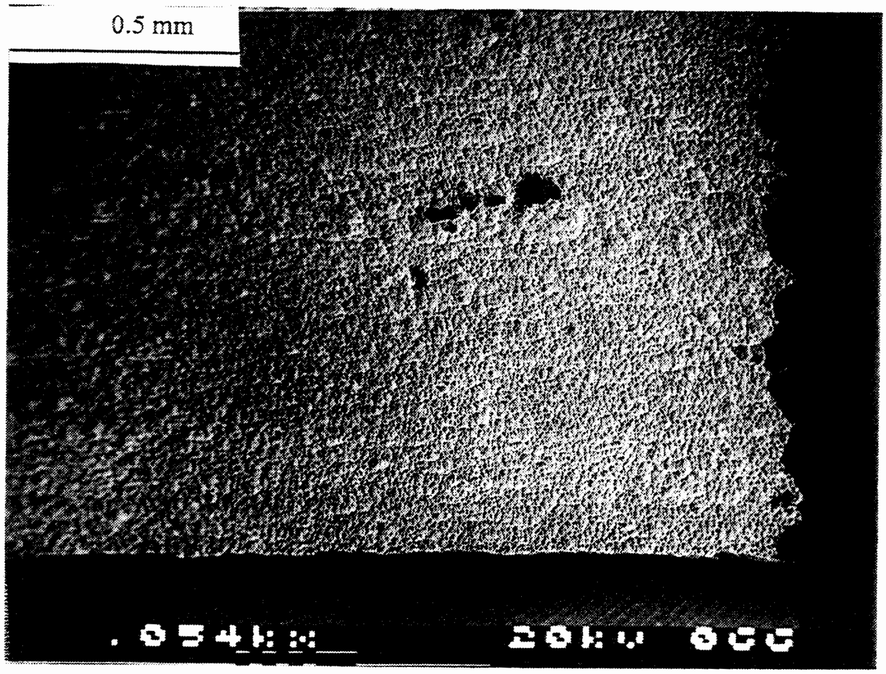


Figure 13. The same edge as in Figure 9 after the electrolysis with almost the same magnification.

There is a change in shape but the spectra of the same regions are almost the same. But after a closer examination near the holes in Figure 12 interesting formations occurred.

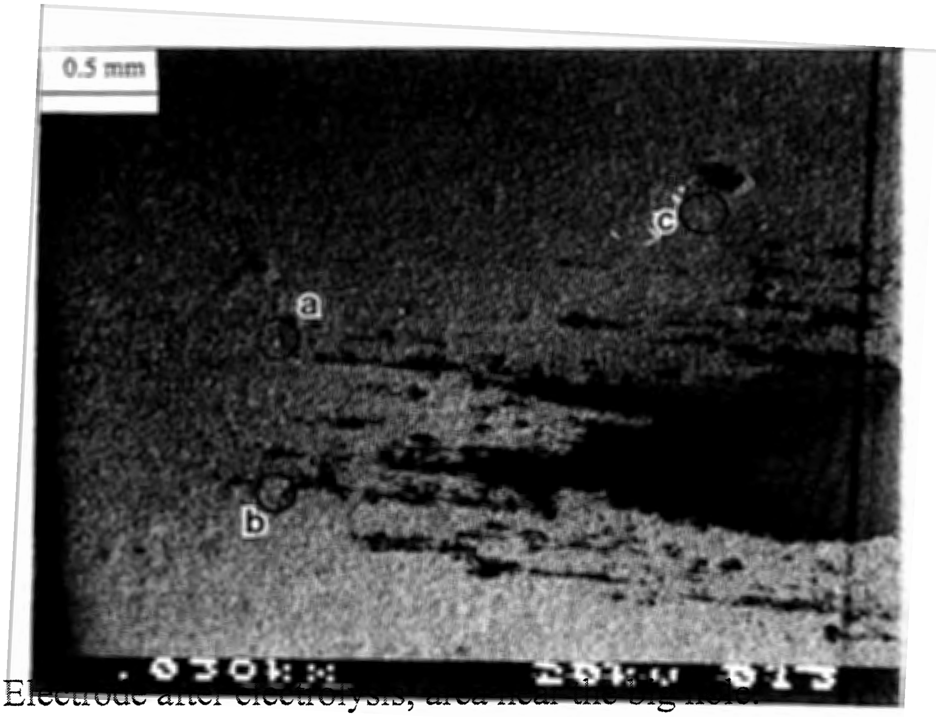


Figure 14. Electrode after electrolysis, area near the big hole.
(wd 10 mm, tilt 45°, mag. 30x)

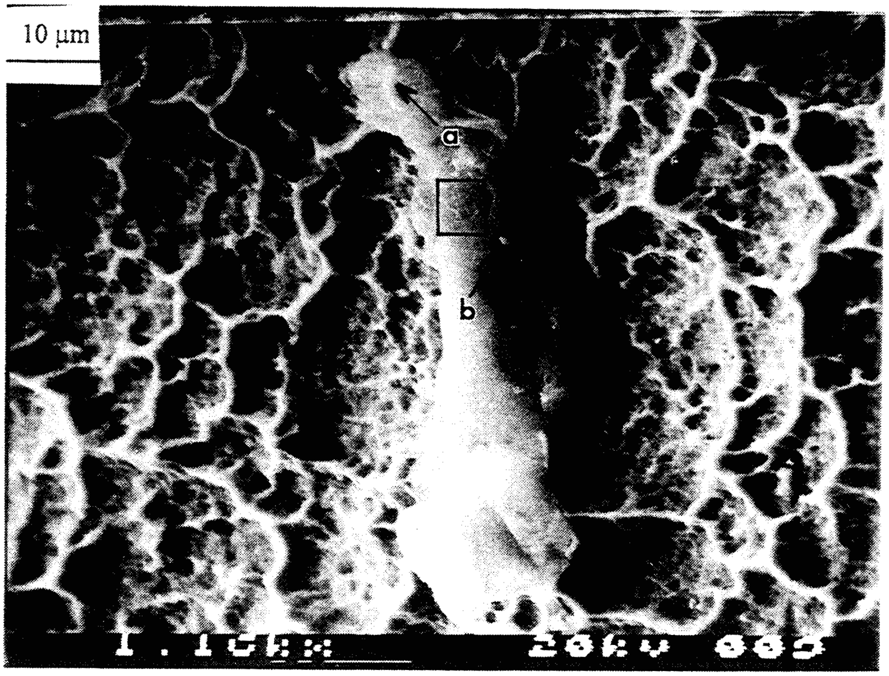


Figure 15. Region (a) from area in Figure 14.
(wd 10 mm, tilt 45°, mag. 1160x)

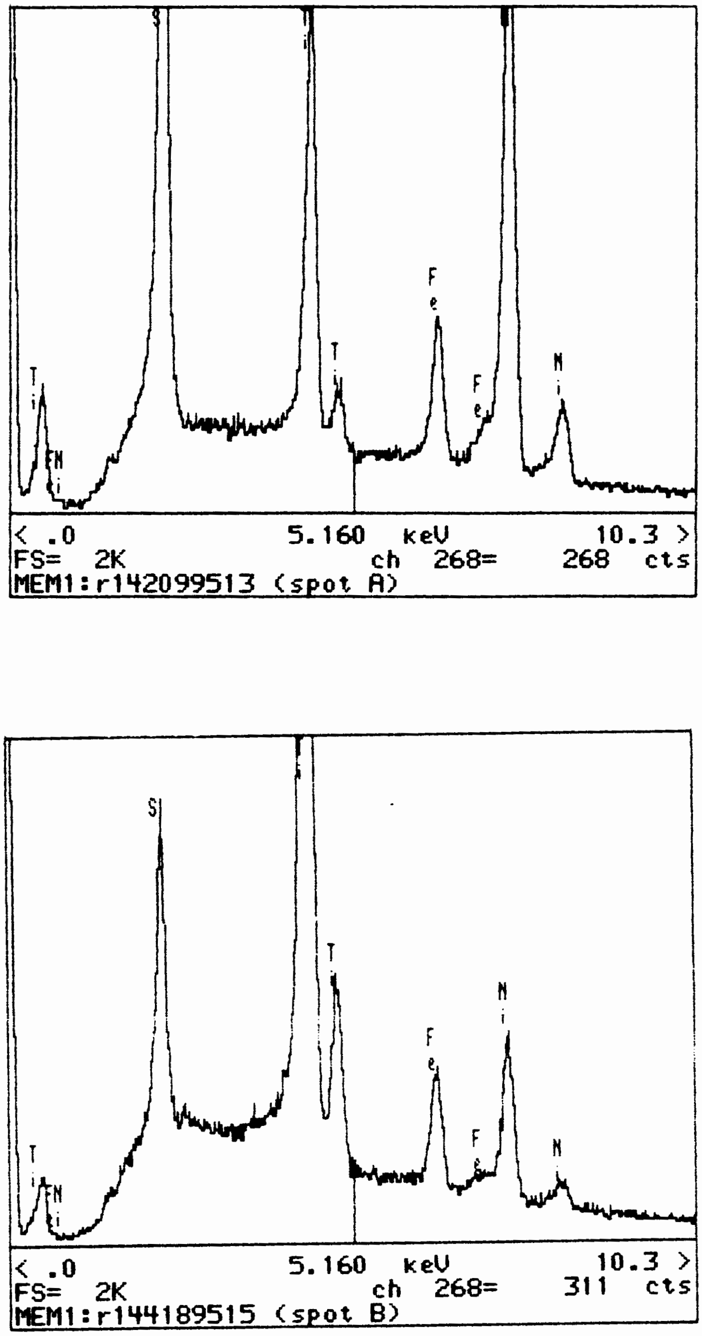


Figure 16. EDS spectra from region (a). (Figure 15)

The unexpected element in this area is nickel. The same element occurs also in many other regions for example in region (b).

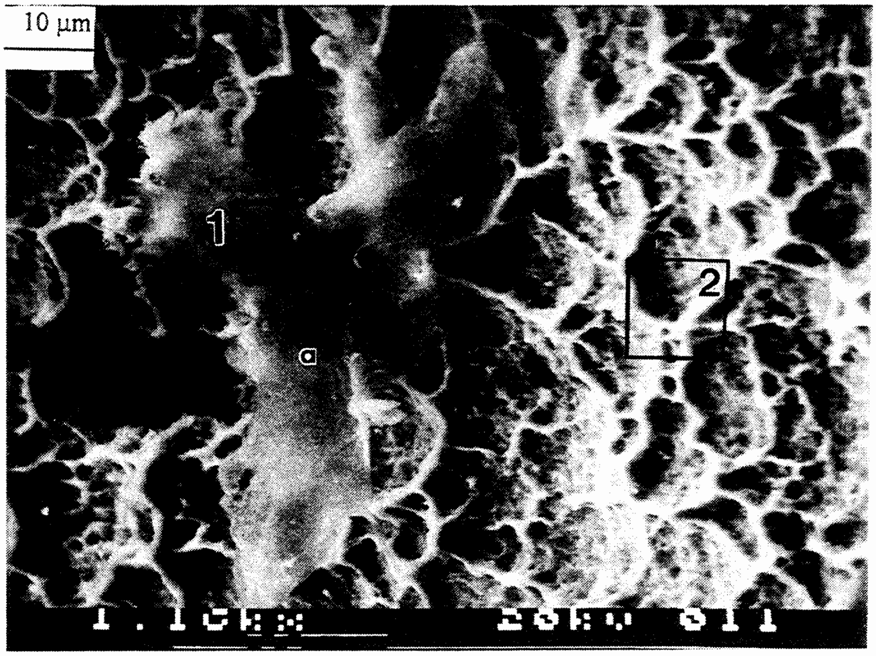


Figure 17. Region (b) from area in Figure 14.
(wd 10 mm, tilt 45°, mag. 1160x)

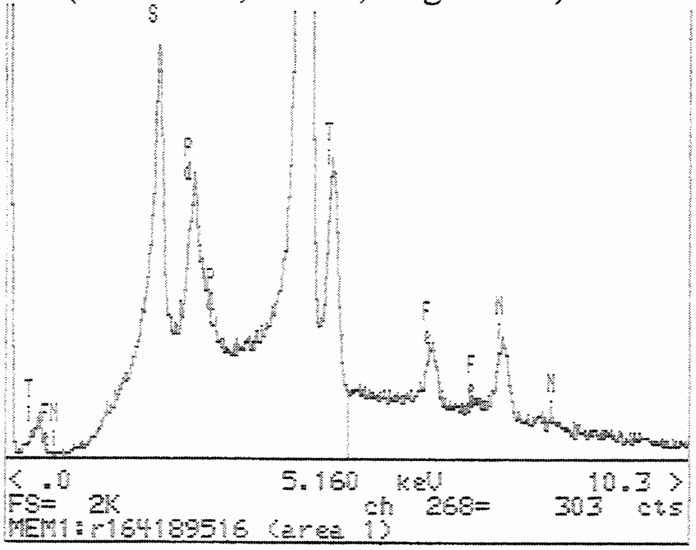


Figure 18. EDS spectrum from region (b).

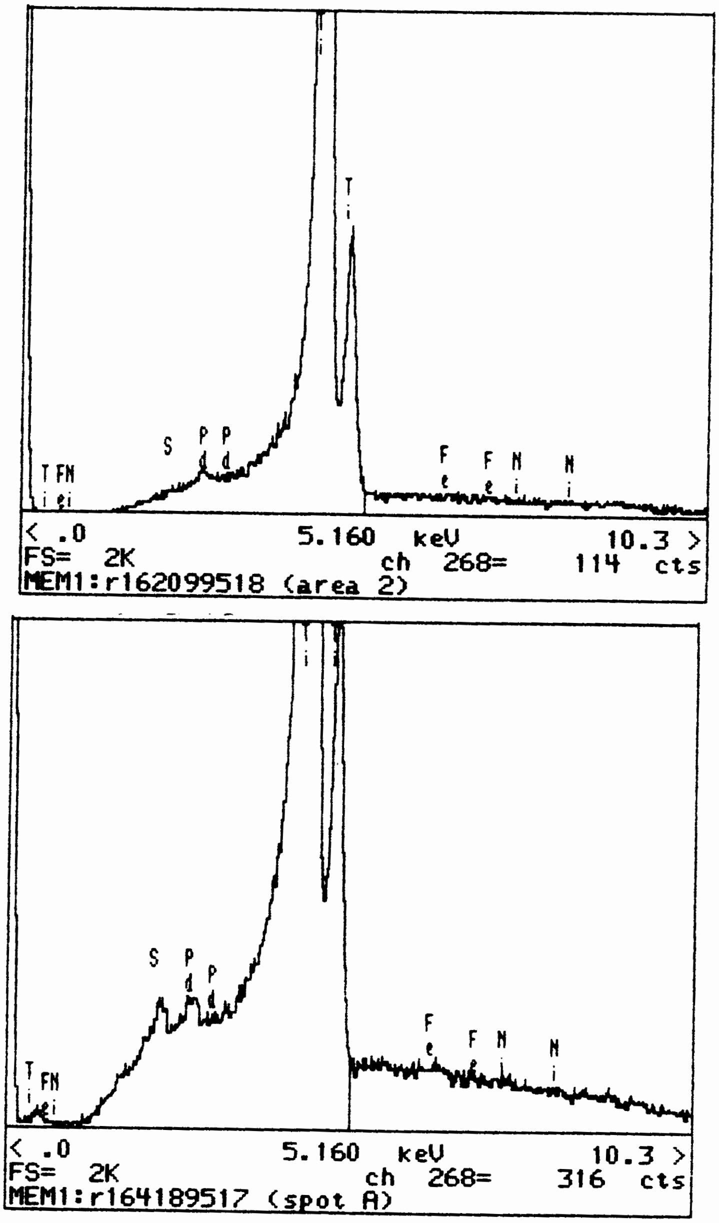


Figure 18. EDS spectra from region (b). (continued)

Ni has a very strong peak even when the area mode is used. Fe is always present.

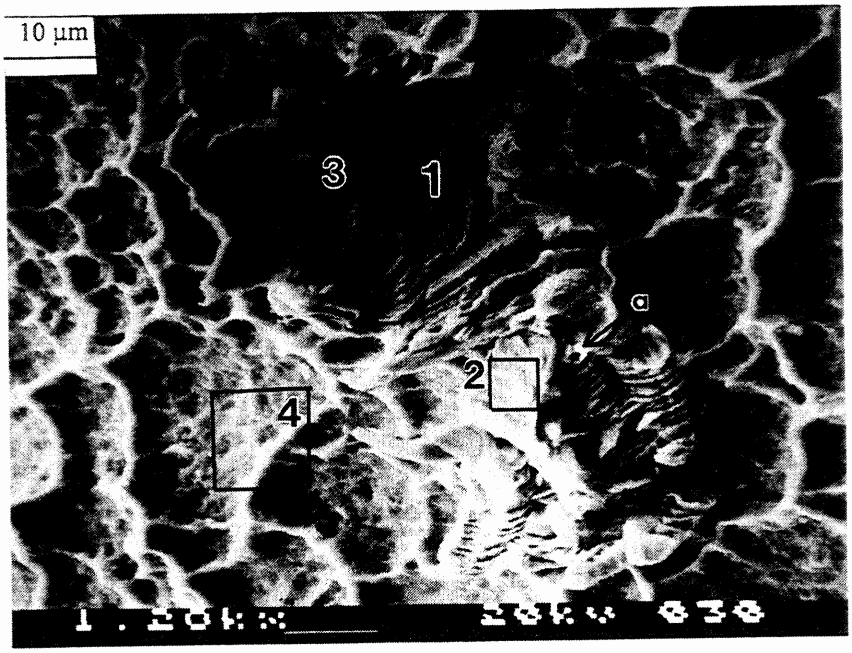


Figure 19. Region (c) of area marked in Figure 14.
(wd 10 mm, tilt 45°, mag. 12800x)

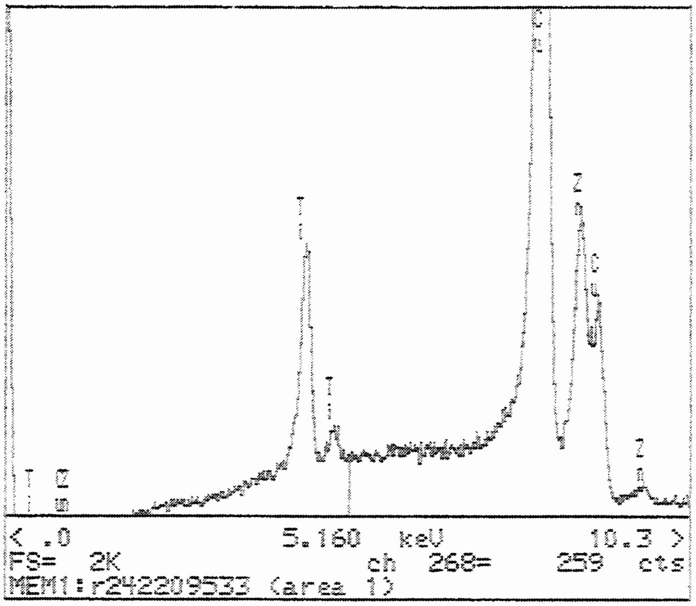
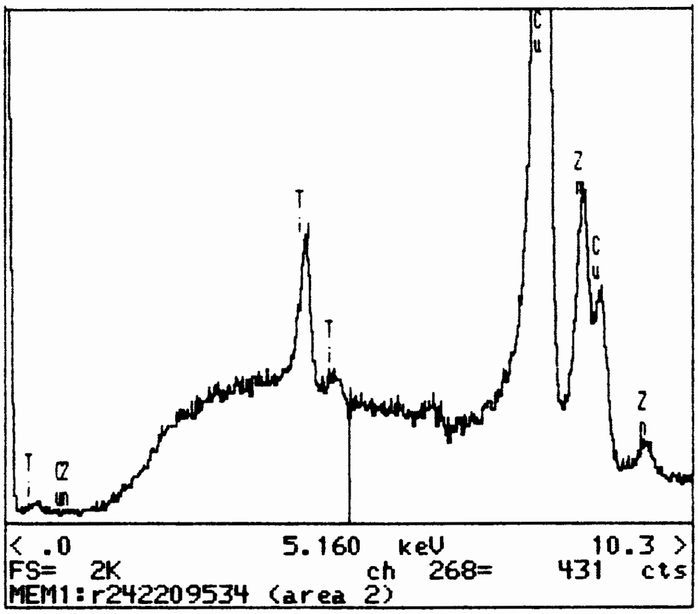


Figure 20. EDS spectrum from region (c).



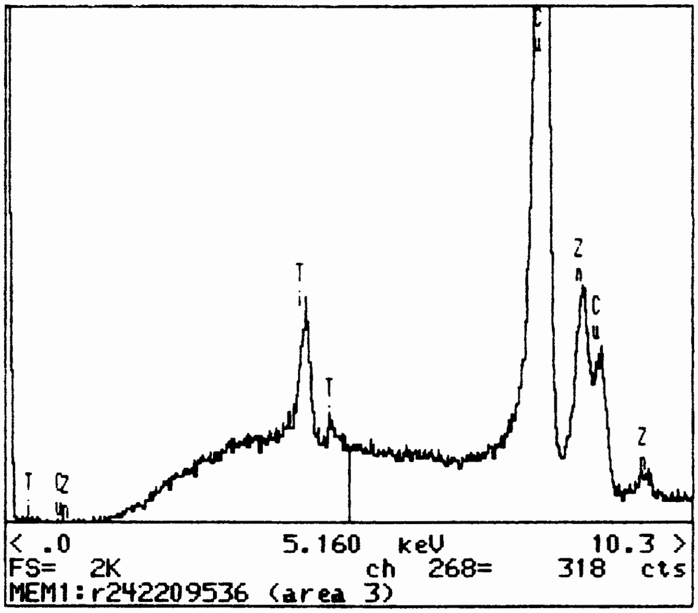
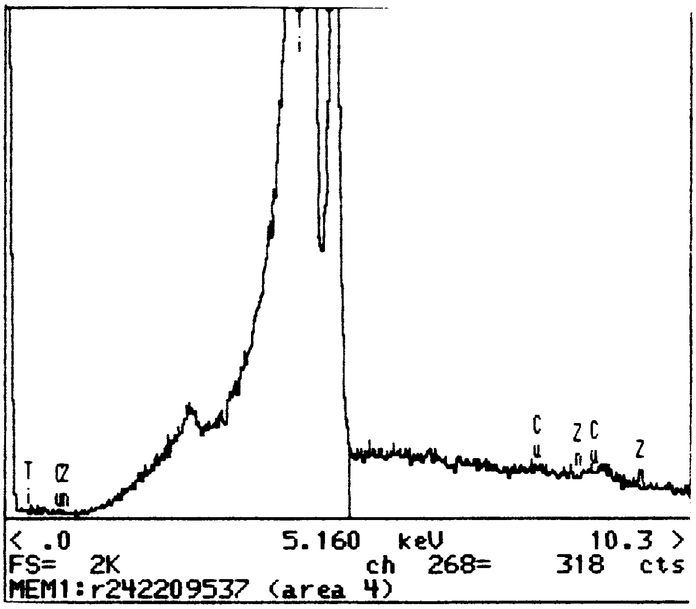


Figure 20. EDS spectra from region (c). (continued)



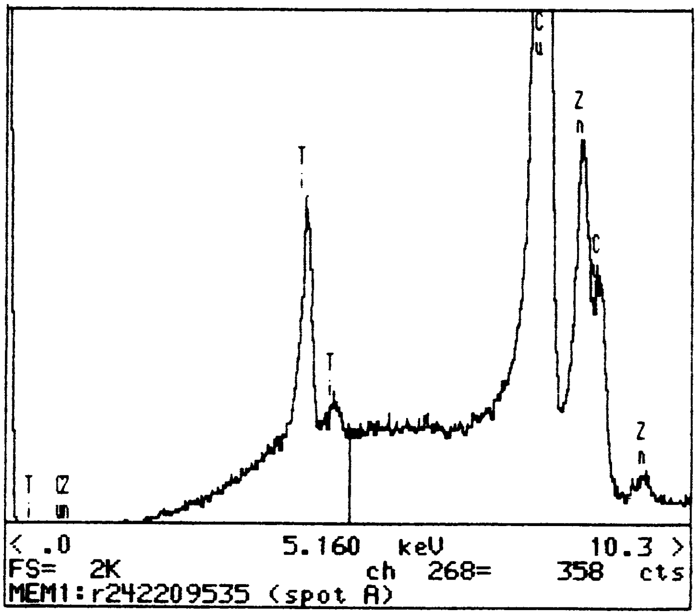


Figure 20. EDS spectra from region (c). (continued)

Zn and Cu have been found in this region. Cu has a possible source from spot welding but Zn was unexpected.

There have been many similar areas like these where Ni and Zn was found. Ni was always in combination with Fe, Zn with Cu.

Results from the first experiment

The radiation and temperature measurements have to be improved in the second experiment. The experiment has to last longer (exposure for the TLD chips), cell voltages have to be stabilized, more thermocouples will be used and the data will be recorded with computers.

For the morphology and microanalysis of the Ti cathode, the concentration of the electrolyte will be lowered. This makes it possible to clean the cathode after the experiment ultrasonically in deionised water. In this experiment Ni, Fe and Zn have been found as unexpected elements on the titanium cathode. Ni occurred in combination with Fe, Zn with Cu. It is unclear if Fe is a result of contamination or occurs in a larger quantity as before electrolysis. The strong palladium peak in Figure 18 was the only large location of this element. No other region was found.

SECOND EXPERIMENT

Experience from the first experiment was helpful to run the second one for the time desired. For this reason the concentration of the sulfuric acid had to be lowered to 0.01 mol fraction. Because of the high loss of the electrolyte in the previous experiment 15 ml were used in each cell and the cells were sealed better than before. The total time for this electrolysis was 54 hours. It was also possible to stabilize the voltages in each cell: therefore the temperature calculation was doable. Six thermocouples instead of one were used.

The electrolytic cells were connected in series again supplied by 0.55A. The current was also decreased to avoid a large loss of electrolyte. For this reason the area of the cathodes had to be decreased to obtain still a current density of 2 A/cm^2. The cell voltages and all temperatures were monitored continuously.

In addition to the chips, two Geiger-Mueller counters were used to measure the radiation of both cells. Background measurements were done after the experiment. The data from the Geiger-Mueller counters were also collected with computers.

Temperature

Every component of the D cell was made heavier for the same reason as in the first experiment. Six thermocouples were used on the outside of each cell, one thermocouple was collecting the room temperature. The placement for each thermocouple can be seen below.

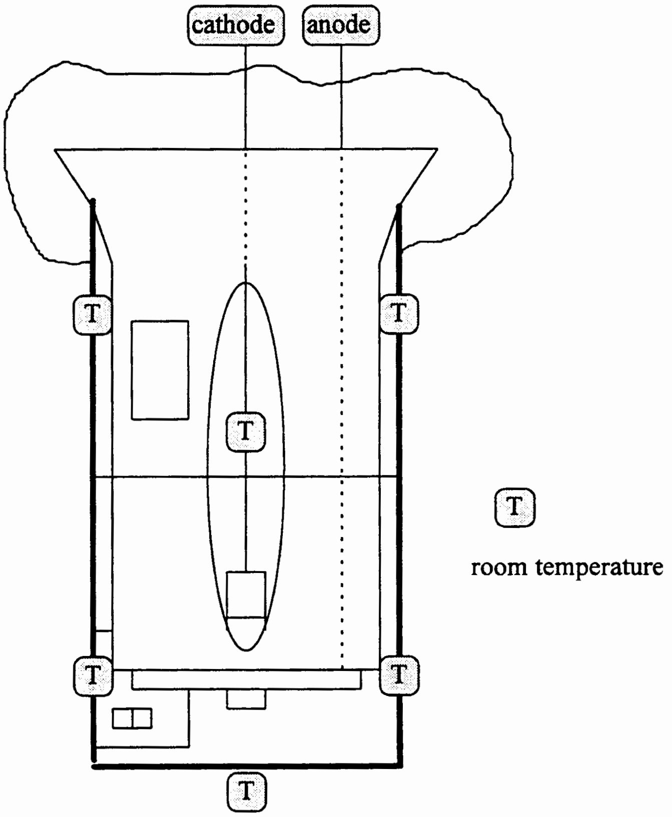


Figure 21. Placement of the six thermocouples on the outside of the cells. (D and C cell)

The measurement of temperature was performed for 33 hours, collecting data every 5 seconds. After 23 hours the C cell was taken out of the circuit (too much loss of electrolyte; the difference between D and C cell was 1.5 ml) but for the D cell the collection continued. For the evaluation of the data, the average of all thermocouples for each cell was taken (data are listed in the appendix) . The standard deviation of the average just shows how homogeneous the temperature distribution was and does not play any important role in the evaluation because each thermocouple was showing a higher temperature in the D cell almost without exception. With given voltage, the power input was calculated as P = I *V. The graphs for temperature and power input during 33 hours can be seen below:

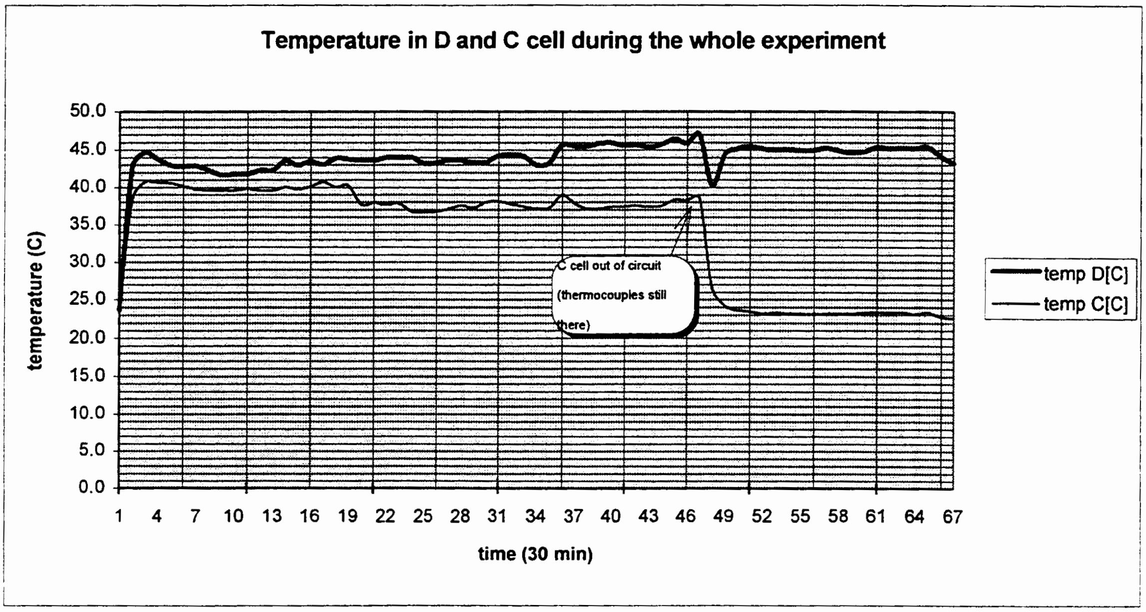


Figure 22. Temperature in D and C cells during the whole experiment.

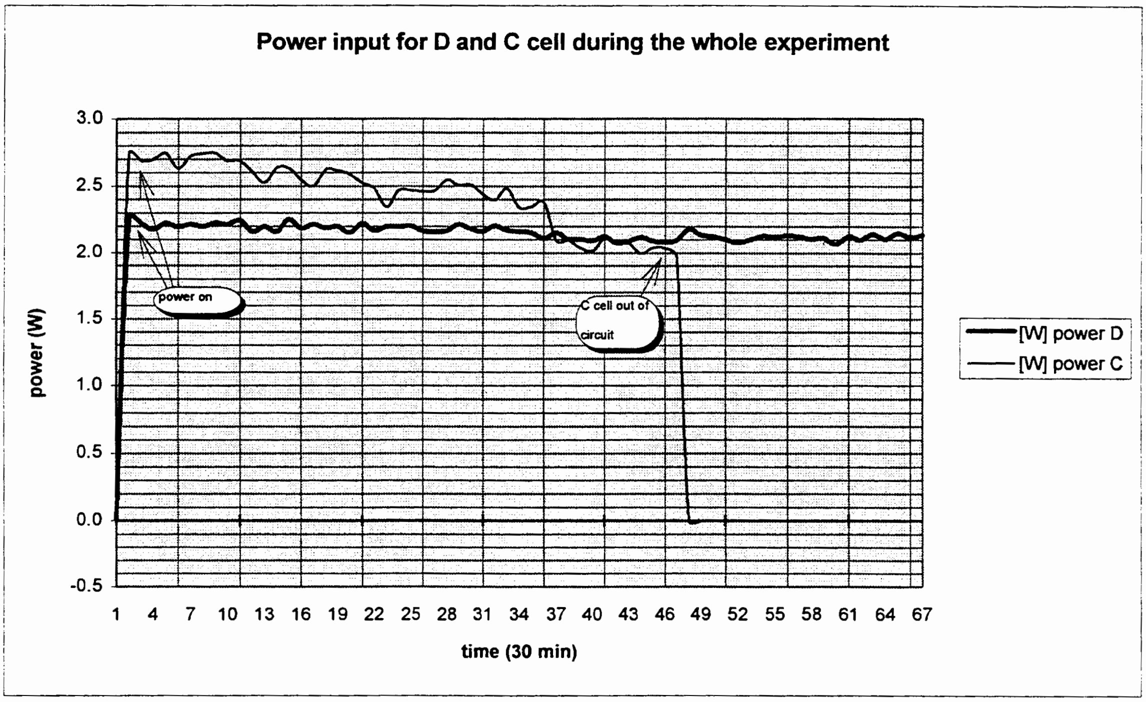


Figure 23. Power input for D and C cells during the whole experiment.

As we can see, the average temperature of the D cell was higher all the time although the power input was lower for almost 18 hours. We will look at the beginning of those graphs more precisely.

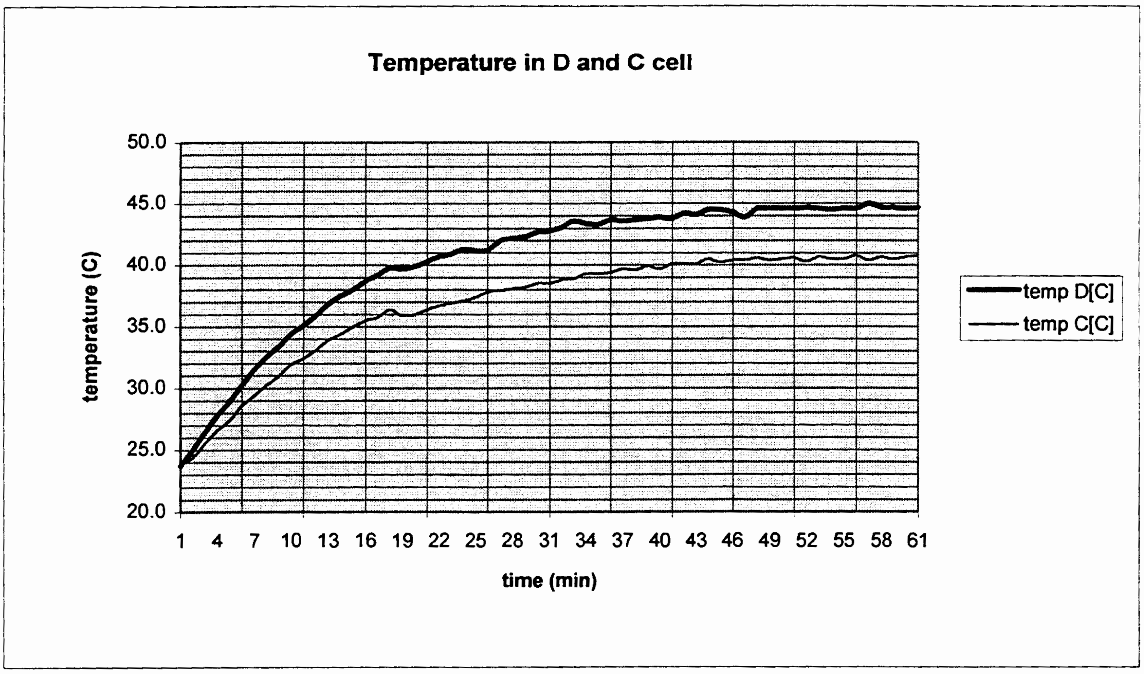


Figure 24. Temperature in D and C cells during the first hour.

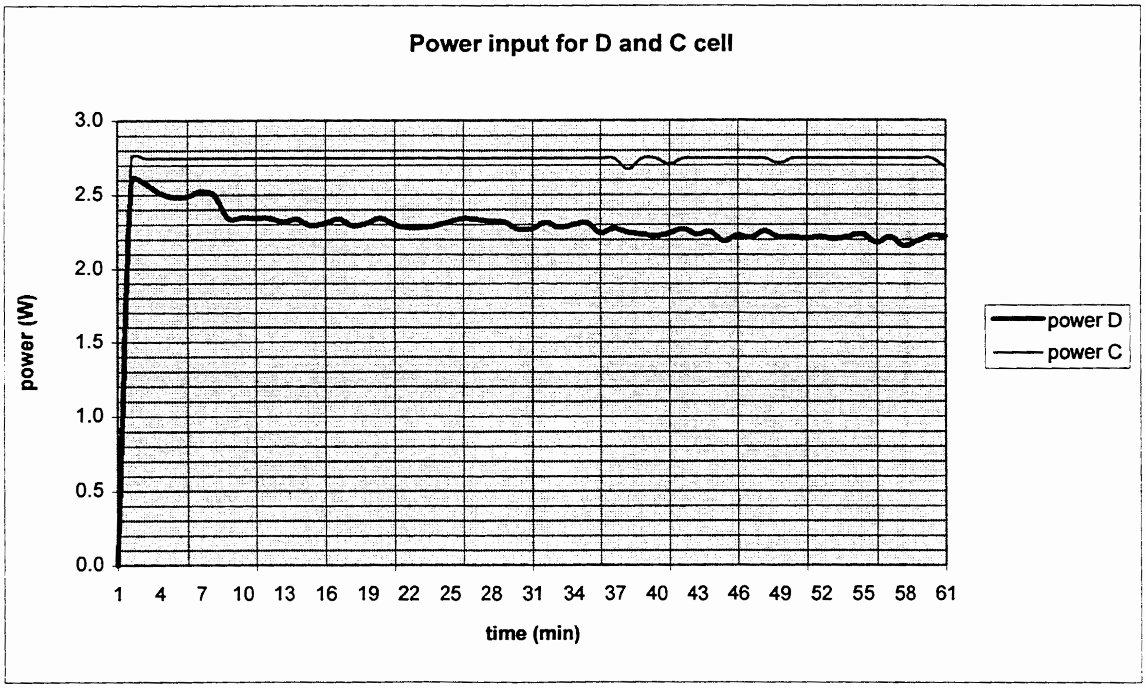


Figure 25. Power input for D and C cells during the first hour.

Above we see the temperatures and power input for both cells during the first hour. The decrease of the power input during the experiment despite the constant current is due to the increasing temperature of the cells. This means that the resistance is decreasing (theory in experiment 1). The temperature in the D cell is higher from the beginning on. After 22 minutes the difference is 4 °C. The power input into the D cell is lower all the time. The difference is up to 0.5 W. This can be seen more clearly when the temperatures and power inputs from both cells are subtracted (D-C), as shown in Figure 26.

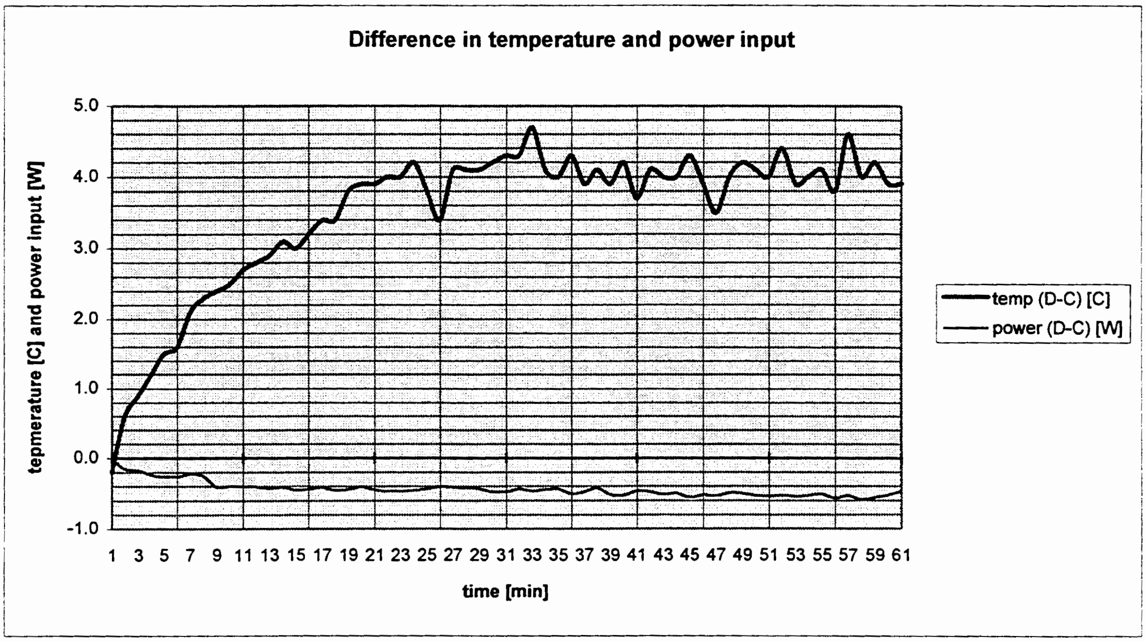


Figure 26. Difference in temperature and power input during the first hour.

The question is if the difference in temperature does not result just from the larger electrolyte loss in the C cell and from the heat of formation of titanium hydride. An estimation calculation can be carried out. Conservative assumptions are used.

The three terms that contribute to the formation of heat in the D cell are the formation of titanium deuteride, the power input and possibly the heat due to cold fusion. The C cell has just the second term. The heat loss in both cells is due to the heat transferred to the surroundings and to evaporation of electrolyte ($\Delta H_{vap}(D_2O) \approx 10.5$ kcal/mole) or loss of the recombination enthalpy of $D_2 + 1/2\ O_2 \rightarrow D_2O$, ($\Delta H \approx 57$ kcal/mole) on the catalyst. Since the last term is larger, it is employed in the calculations. The following equations give the rate of enthalpy change in each cell:

D cell: $dH_D/dt = H_{C.F.}/dt + H_{TiD}/dt + V_D I - H_{vap}(D)/dt - \alpha \Delta T_D$

C cell: $dH_C/dt = V_C I - H_{vap}(C)/dt - \alpha \Delta T_C$,

where H_D is the enthalpy content of the cell,

$H_{C.F.}$ is the enthalpy released by cold fusion,

H_{vap} (D) is the recombination enthalpy lost by D_2 and O_2 escape from the D cell,

H_{TiD} is the enthalpy from the formation of the TiD,

V_D is the cell voltage of the D cell,

I is the current through each cell,

α is the rate of heat loss by the cell to its surroundings, and

ΔT_D is the difference in temperature between the cell and the surrounding.

The terms with subscript C have the same meaning for the C cell.

At steady state both equations can be set equal to 0. Since the cells are the same the second equation can be solved for α and plugged into the first one.

$$\Rightarrow H_{C.F.}/dt + H_{TiD}/dt + V_D I - H_{vap}(D)/dt - \Delta T_D/\Delta T_C(V_C I - H_{vap}(C)/dt) = 0$$

Out of this equation it can be calculated if there is any positive “cold fusion” term. For E_{TiD} and E_{vap} some estimation calculations have to be done. After 45 minutes the temperature in both cells reaches steady state.

ΔT_D is 20.6 °C and ΔT_C amounts to 16.5 °C. Therefore the quotient is 1.25. If we consider our calculations for one hour steady state, the energy input into the D and C cell is:

$$V_D It = 7200\ \text{J} = \underline{1720\ \text{cal}}$$

$$V_C It = 9000\ \text{J} = \underline{2150\ \text{cal}}$$

The electrolyte loss in the D cell was 1.5 ml during 33 hours, i.e. 0.045 ml per 1 hour or $2.5 * 10^{-3}$ mol D_2O. If we consider the worst case that the D_2O split and escaped as follows:

$$D_2O \rightarrow 1/2\ 0_2\uparrow + D_2\uparrow$$

Then the enthalpy for splitting is approximately 57,000 cal/mol 15).

With this information the enthalpy that was carried away can be calculated to be:

$$H_{vap}\,(D) = 57 * 10^3\ \text{cal/mol} * 2.5 * 10^{-3}\ \text{mol} = \underline{142.5\ \text{cal}}\ .$$

In the C cell the loss during the 33 hours amounted to 3 ml

$$\Rightarrow H_{vap}\,(C) = 57 * 10^3\ \text{cal/mol} * 5 * 10^{-3}\ \text{mol} = \underline{285\ \text{cal}}$$

The last missing enthalpy in our problem is the enthalpy that is being released in the D cell during the formation of the titanium hydride. Some estimation calculations can be carried out, again with consideration of the worst case.

The free enthalpy is approximately given by $\Delta H = -29.5$ kcal/mole.[2)] This means this is an exothermic reaction. This is the worst case when the titanium is "loaded" completely. The mass of the cathode at the beginning of the experiment was 0.0625 g. We assume that the "loading" lasts the whole experiment and is linear. After one hour, $3.95 * 10^{-5}$ mole Ti is converted into TiD_2.

$$\Rightarrow H_{TiD} = 29.5 \text{ kcal/mole} * 3.95 * 10^{-5} \text{ mole} = 1.17 \text{ cal}$$

We can put all energies that have been estimated into our equation:

$$H_{C.F.} + 1.17 \text{ cal} + 1720 \text{ cal} - 142.5 \text{ cal} - 1.25 * (2150 \text{ cal} - 285 \text{ cal}) = 0$$

$$\Rightarrow H_{C.F.} = \underline{751.15 \text{ cal}}$$

We can see that the enthalpy for TiD formation is negligible. This means that we have at least 750 cal energy per one hour released out off the D cell that can not be explained, an energy gain of 44% (750/1720).

Radiation

To prevent the Li chips from contact with the electrolyte, the chips were sealed into two polybags. In addition to the chips, two Geiger-Mueller counters placed behind each cell were used for the detection of radiation.

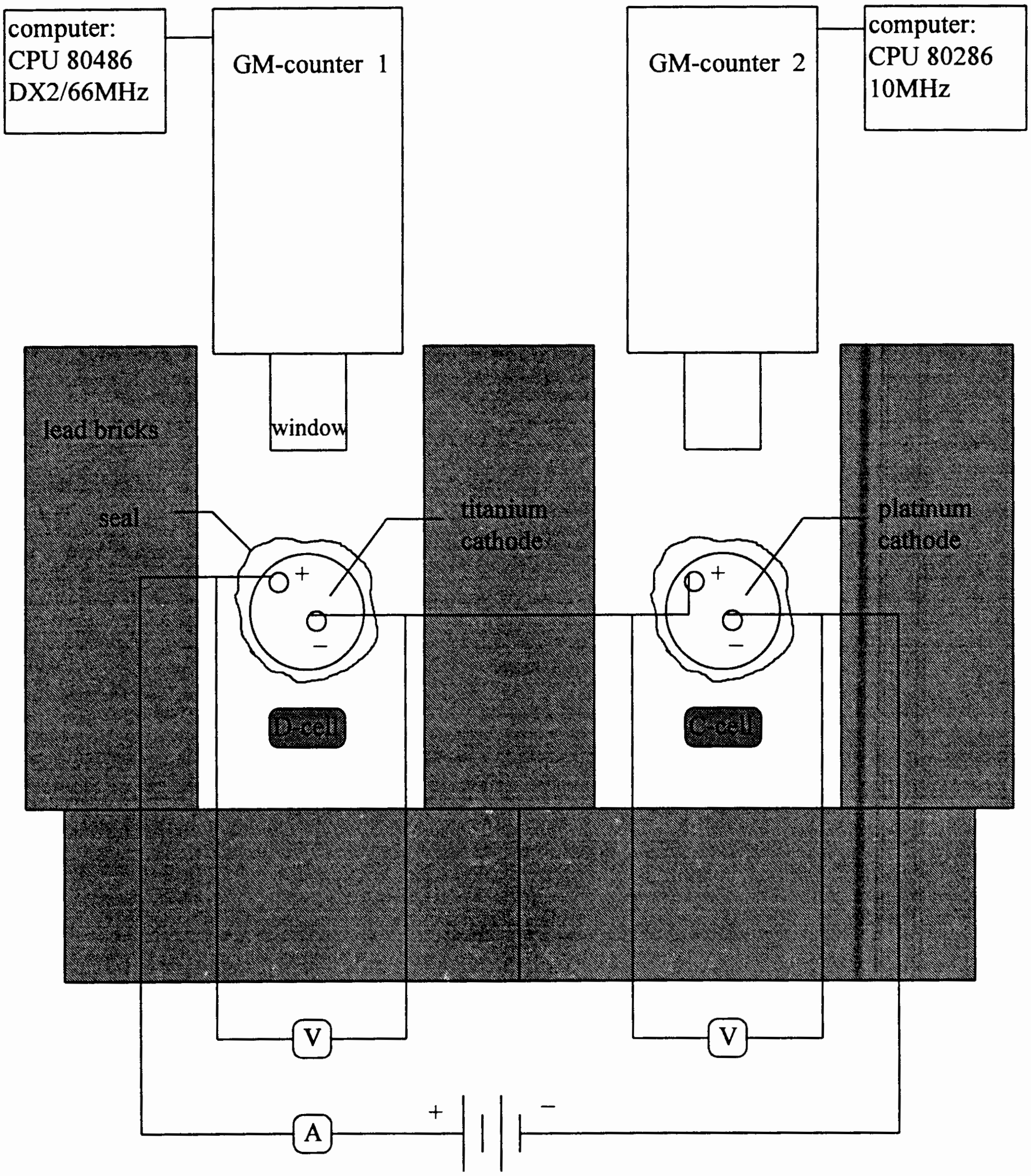


Figure 27. Placement of the Geiger-Mueller counters. (view from top)

The number of counts have been monitored separately every 3 minutes with two computers for a total time of 63 hours which includes time when both cells were disconnected from the circuit. Background measurements have been taken for 45 hours after the experiment. The table for these measurements can be found in the appendix. Average and standard deviation have been calculated for both measurements, Table 2.

counts per h	count1(D)	count2(C)	count1(back)	count2(back)
average	640	617	614	597
st. dev.	28	32	28	28

Table 2. Average in counts per hour and standard deviation for experimental radiation data and background for each cell.

There is a difference of 23 counts per hour during the experiment between the D and C cell, the D cell being higher. But also the counts during the background measurements shows a remarkable difference of 17 counts. The other interesting thing is that the count rate in the C cell during the experiment is also higher than the background taken with the same counter. This suggests that the C cell also produces a small amount of radiation during electrolysis.

The background from the corresponding counter was subtracted from each data point and plotted in a graph with a linear trendline.

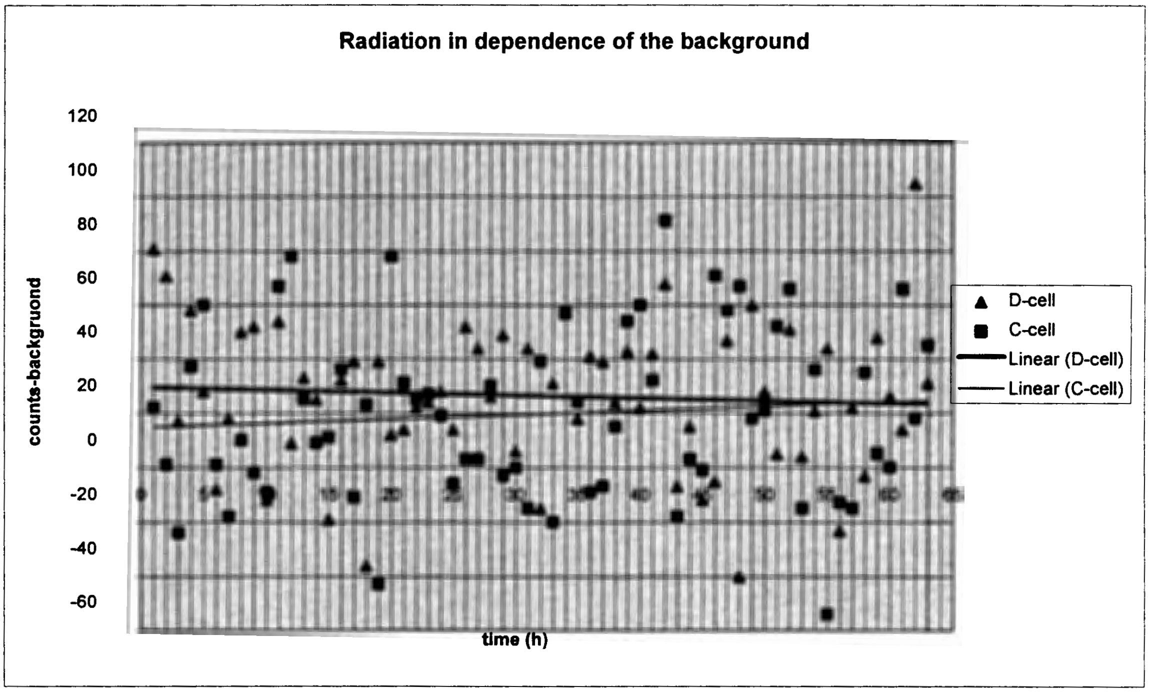


Figure 28. Radiation from each cell. (background subtracted)

Stronger radiation in the D cell is clearly visible. The minimal and maximal counts for this measurement (Table 3) also underline this result.

	D cell	C cell
maximum	150	91
minimum	- 40	- 54

Table 3. Minimal and maximal count rates per hour in both cells minus the background.

For a quantitative consideration, counts per minute have been calculated for every data series (1-5 experiment; 6-8 background).

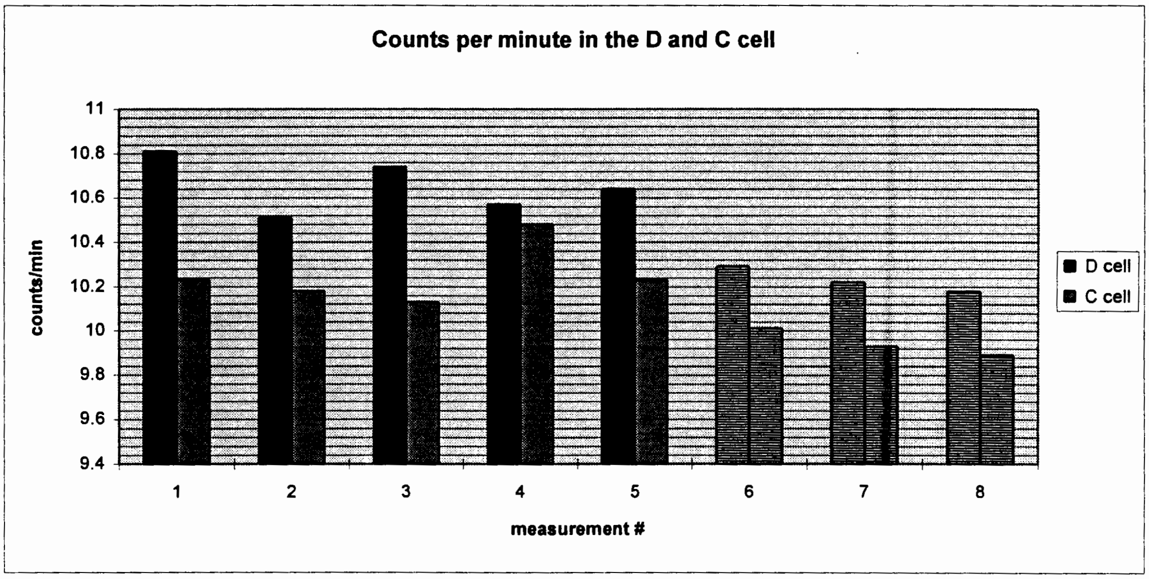


Figure 29. Counts per minute for each cell and for the background.

Each bar gives the average number for a period of 840 minutes from beginning to end of the experiment and for 900 minutes after the power was turned of.

The average counts per minute for the background was calculated and subtracted.

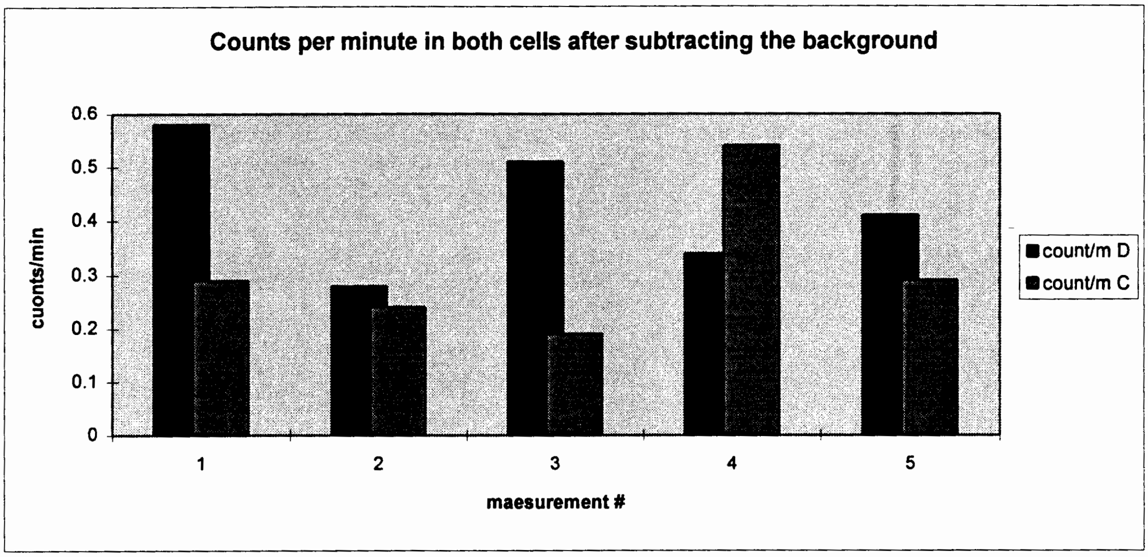


Figure 30. Counts per minute for each cell. (background subtracted)

Each measurement number represents the total counts recorded for each cell over a period of 840 minutes. Only in measurement #4 a higher count rate is visible. The average count rate was calculated.

	D cell	C cell
average counts per minute	0.42	0.31
standard deviation	0.12	0.14

Table 4. Average count rate per minute for each cell. (background subtracted)

The difference between D and C cell amount to 0.11 counts per minute. This means that in 9 minutes there is one event more expected in the D cell. This could be alpha, beta or gamma radiation.

Because the window from the detector can detect only a small part of the radiation that is emitted, other rough estimations can be done. The radius of the window is 0.5 cm, the distance of the cell from the detector 3 cm. With this, the factor was calculated to x = 143. This means 143 counts per 9 minutes or roughly 16 counts per minute more than in the C cell.

The standard deviation is unfortunately too high to be sure about this radiation data. The readings out of the chips are for some reason still under the minimum output for a significant result.

set	TLD	Light Output	^{137}Cs eq mrem
C	600	12	7
	700	6	4
D	600	10	6
	700	3	2

Table 5. Readings out of the TL chips for the second experiment.

The neutron dose would be calculated by subtracting the Li-7 chip ^{137}Cs equivalent from the Li-6 chip ^{137}Cs equivalent and multiplying the difference by a factor which depends on the neutron energy spectrum. The difference in the D cell is 1 mrem more compared to the C cell. But these small exposures do not have any significance. It is suggested to run this experiment with the same devices for even a longer time because of this possible small effect to be measured. If it is possible the experiment should be performed for at least a week.

Morphology and microanalyses of the Ti cathode

The electrode was again untrasonically cleaned in deionised water bath several times (five minutes each time). The same procedure was done with the specimen holder again. The electrode was attached to the holder with a conductive tape. The thin window was in place and the cathode was tilted again for all EDS spectra.

Analysis before electrolyses:

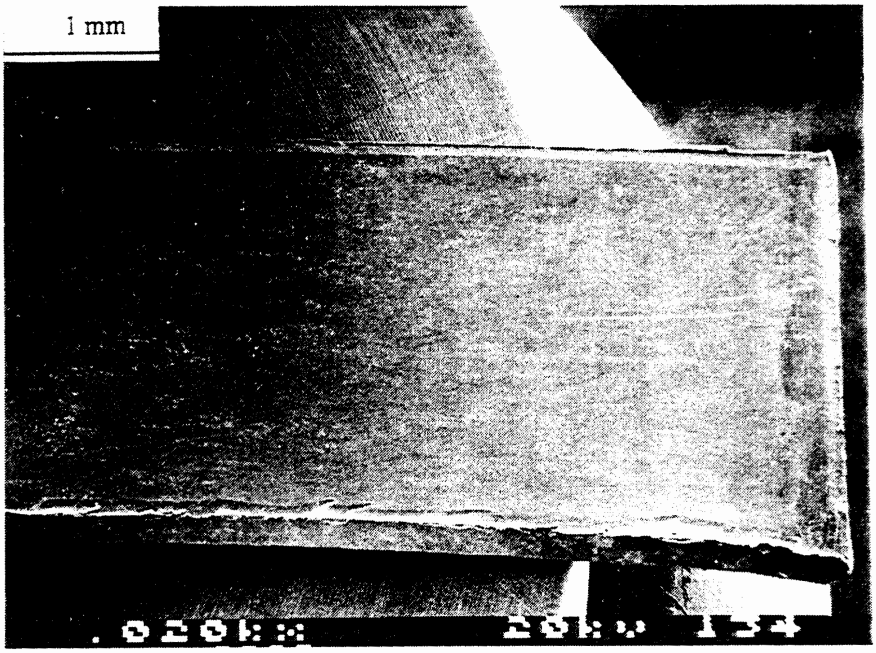


Figure 31. Side 1 of the titanium cathode before electrolysis. (wd 38 mm, tilt 45°, mag. 20x)

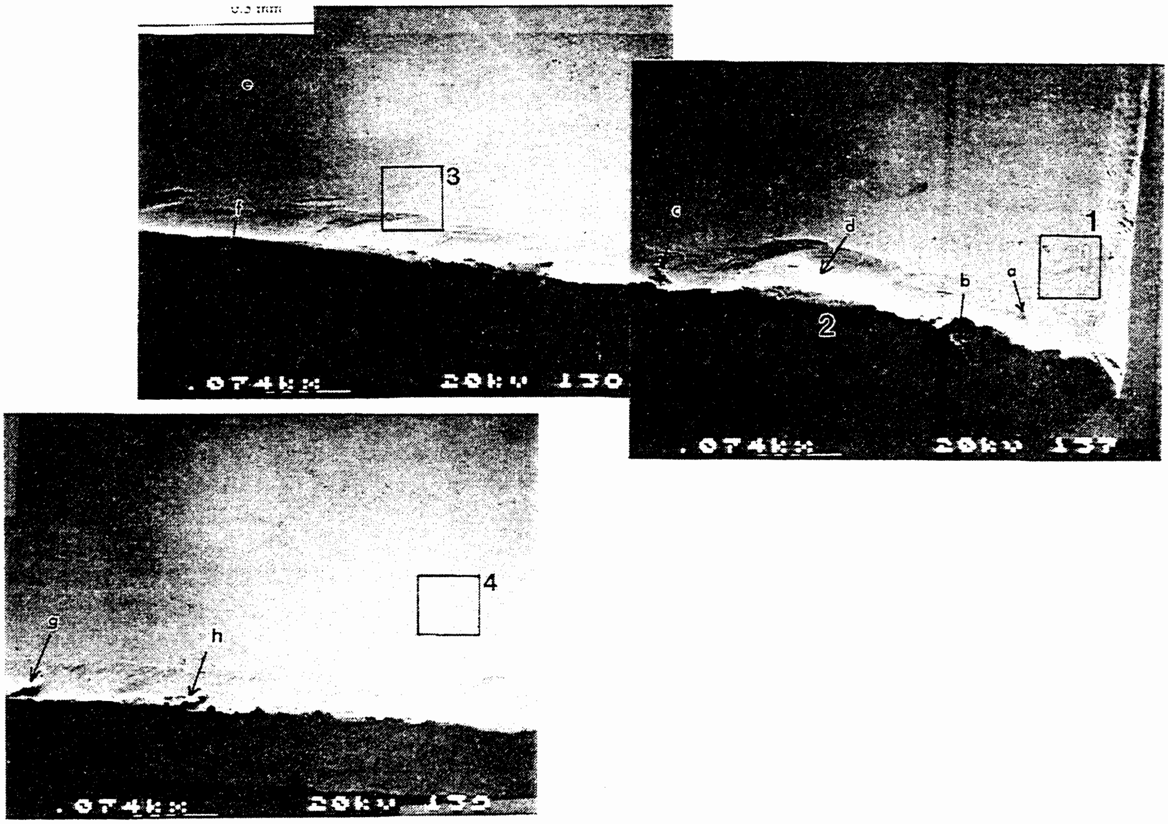


Figure 32. Bottom edge of side 1 before electrolysis.
(wd 10 mm, tilt 45°, mag. 74x)

The following 12 spectra are the EDS spectra from Figure 32.. The acceleration voltage was 20 keV. The only elements detected are elements which are expected due to contamination. Al from the specimen holder, Si can be found everywhere, Cu from spot welding, S and Fe are also not very unusual.

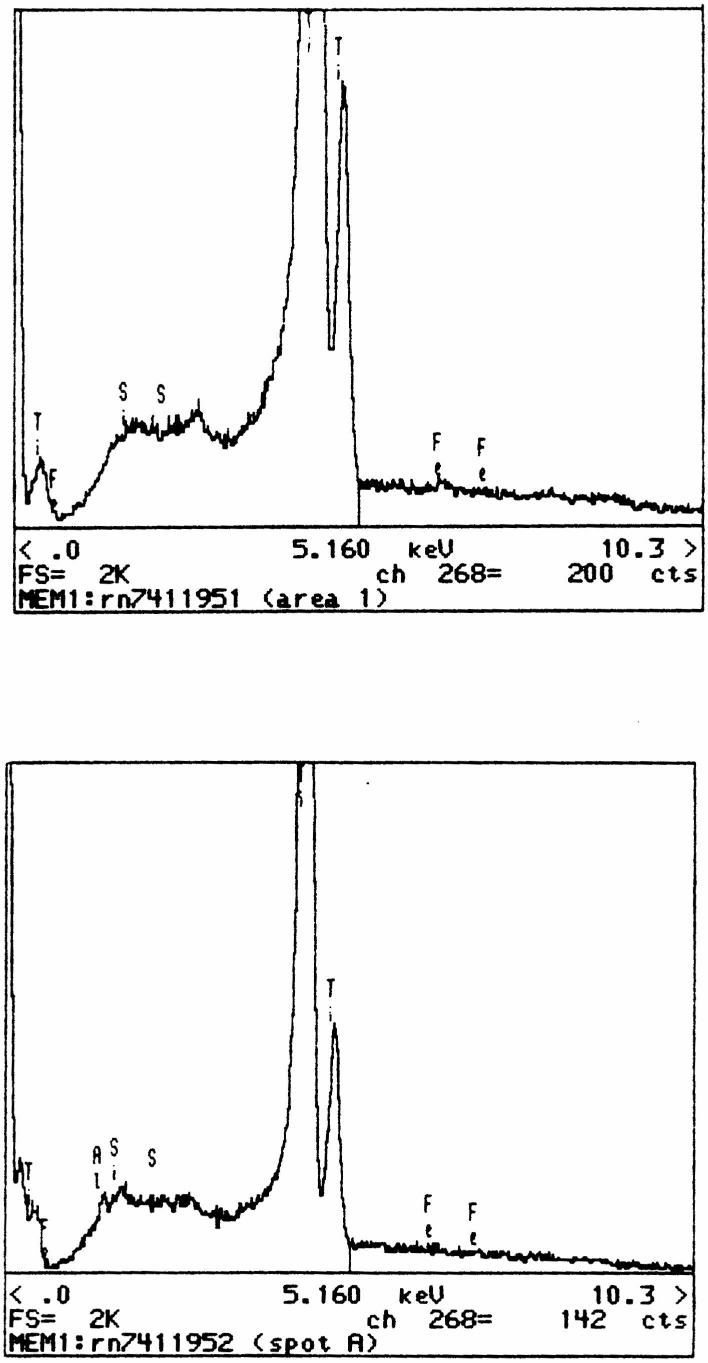


Figure 33. EDS spectra of spots and areas marked in Figure 32.

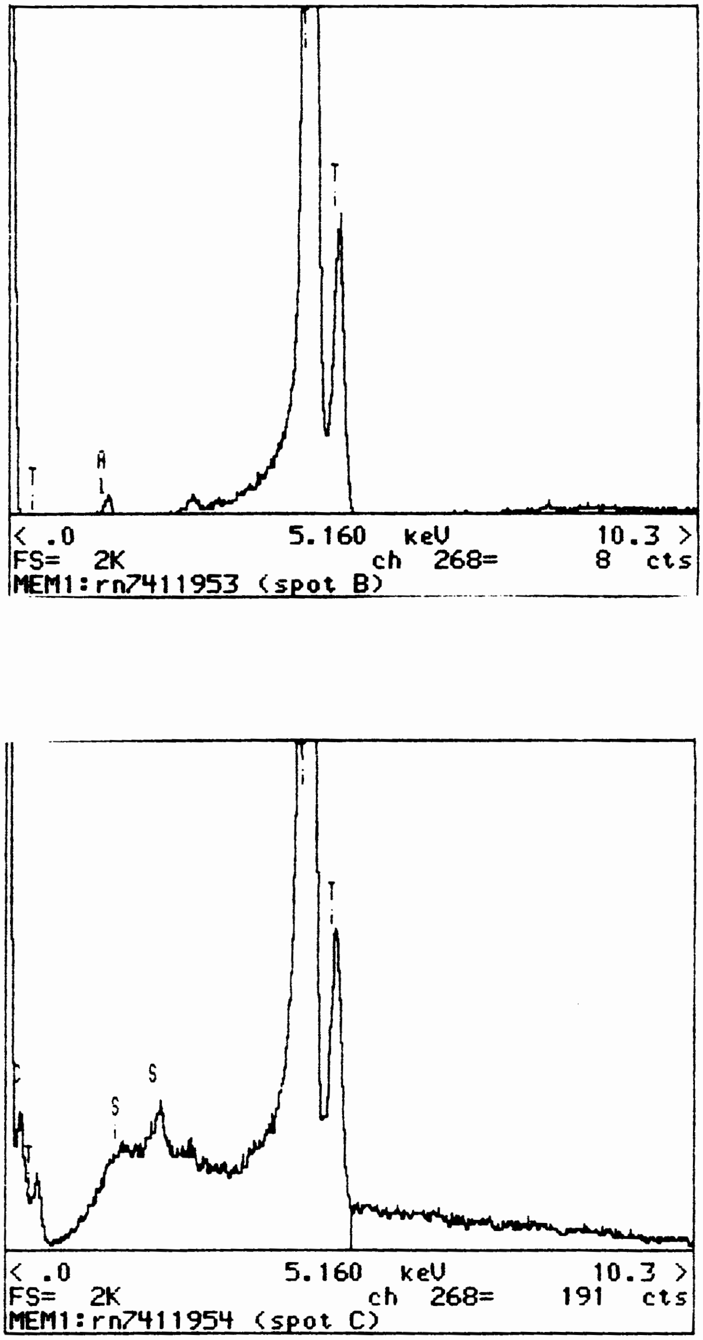
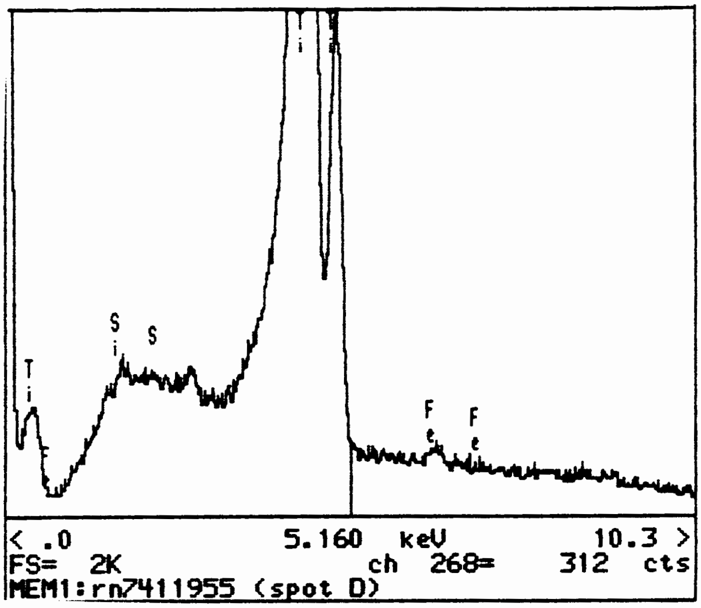


Figure 33. EDS spectra of spots and areas marked in Figure 32.
(continued)



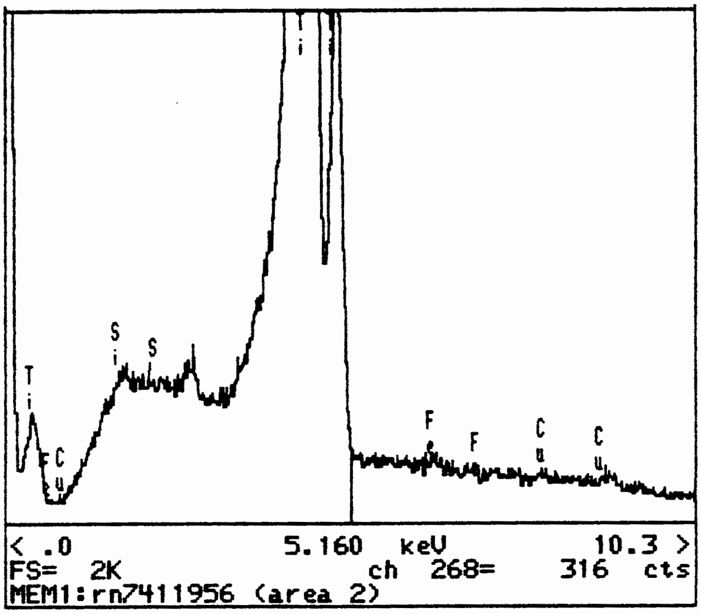


Figure 33. EDS spectra of spots and areas marked in Figure 32.
(continued)

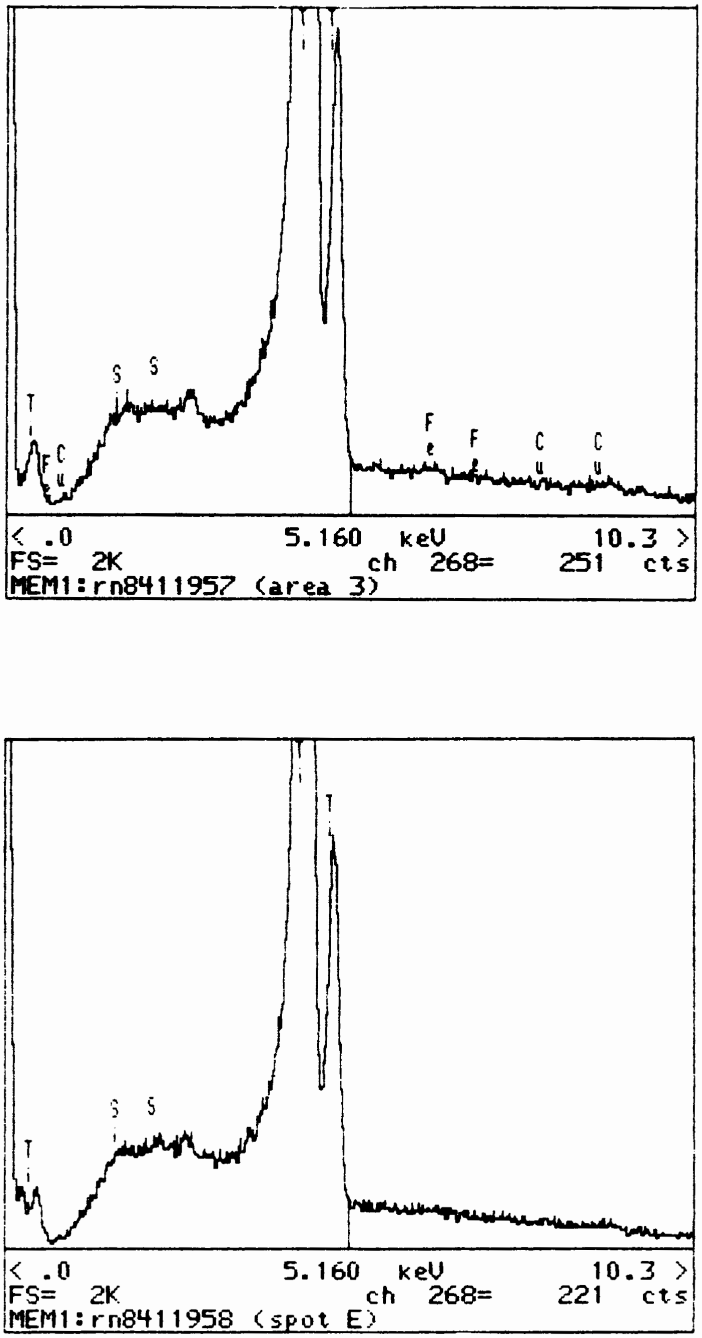


Figure 33. EDS spectra of spots and areas marked in Figure 32. (continued)

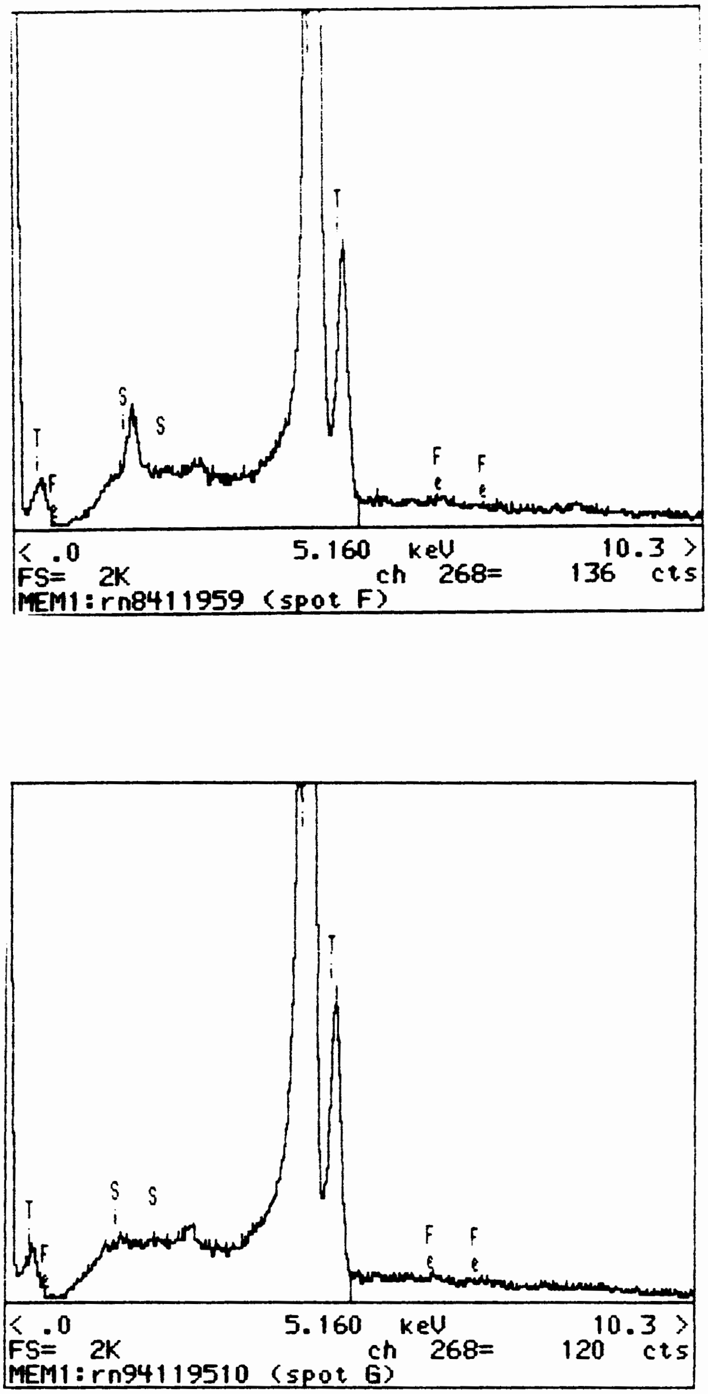
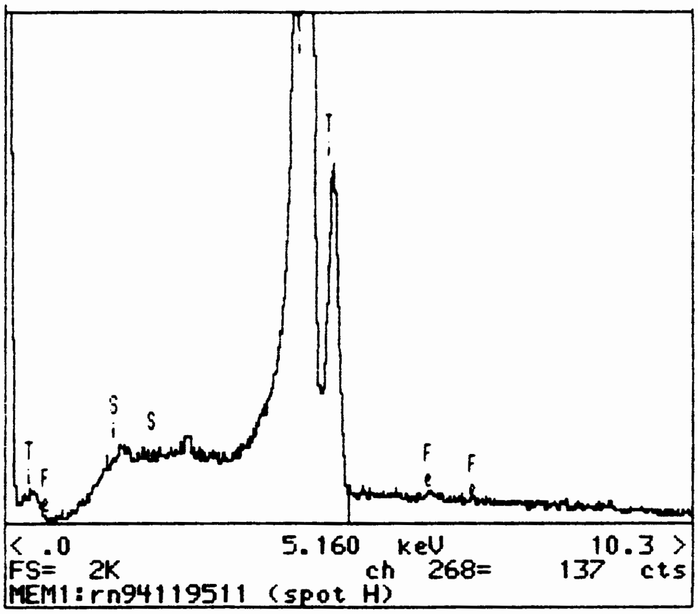


Figure 33. EDS spectra of spots and areas marked in Figure 32. (continued)



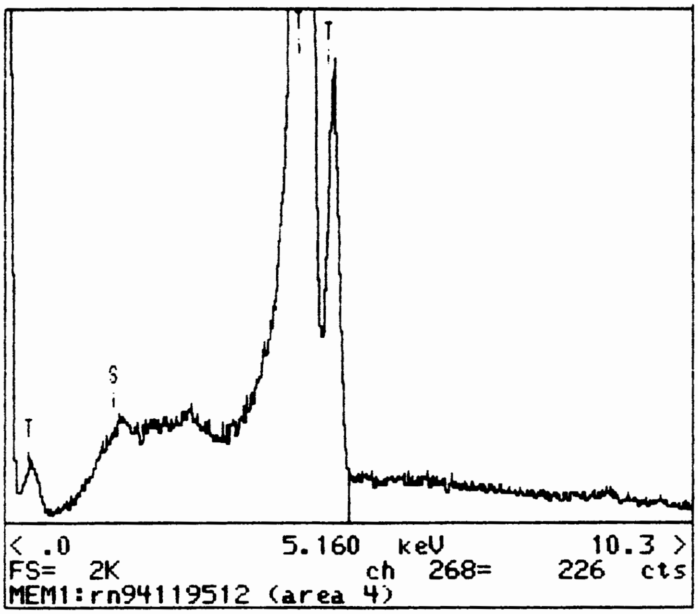


Figure 33. EDS spectra of spots and areas marked in Figure 32. (continued)

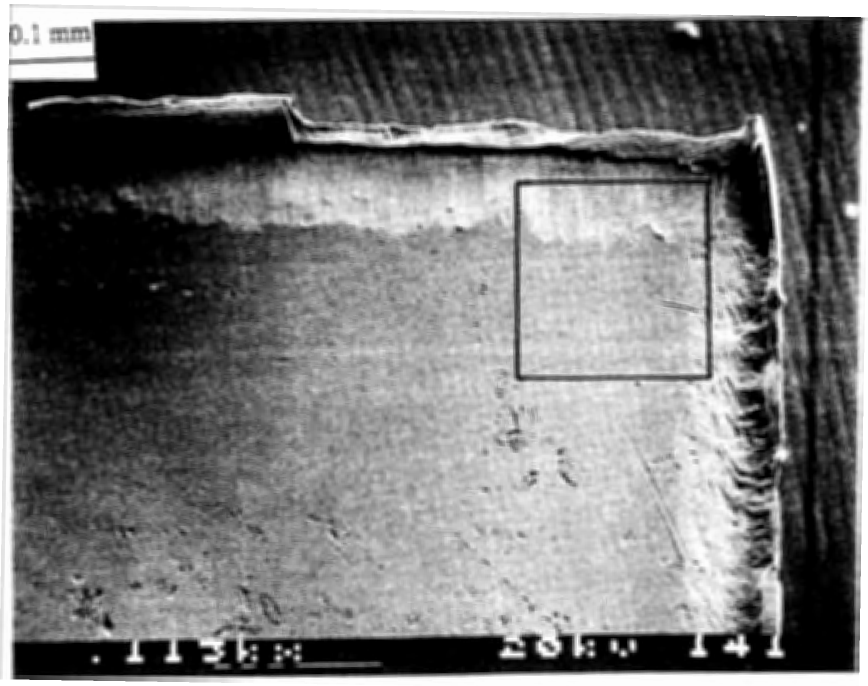


Figure 34. Upper right corner of the first side.
(wd 10 mm, tilt 45°, mag. 113x)

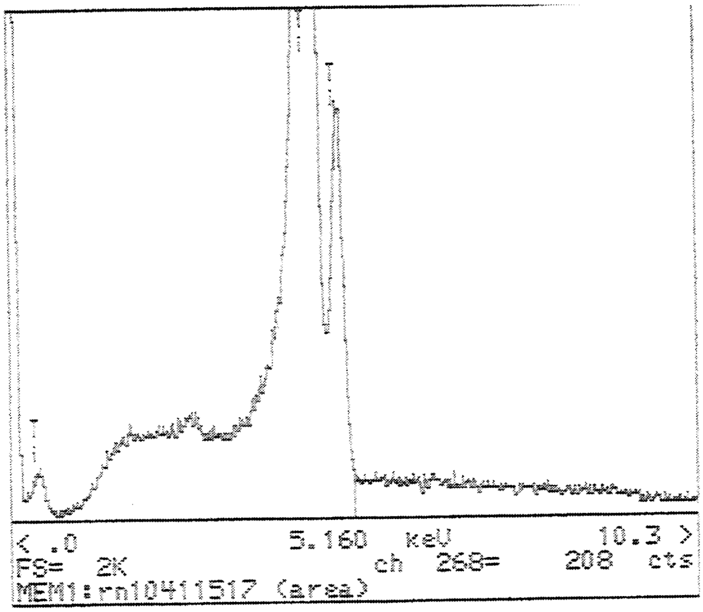


Figure 35. EDS spectrum of area marked in Figure 34.

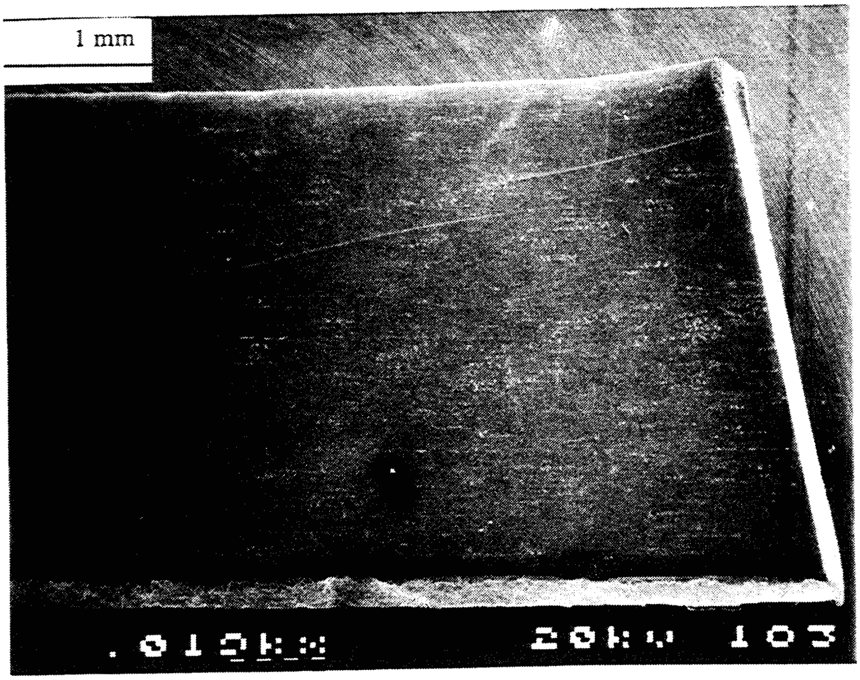


Figure 36. Side 2 of the titanium cathode before electrolysis. (wd 38 mm, tilt 45°, mag. 19x)

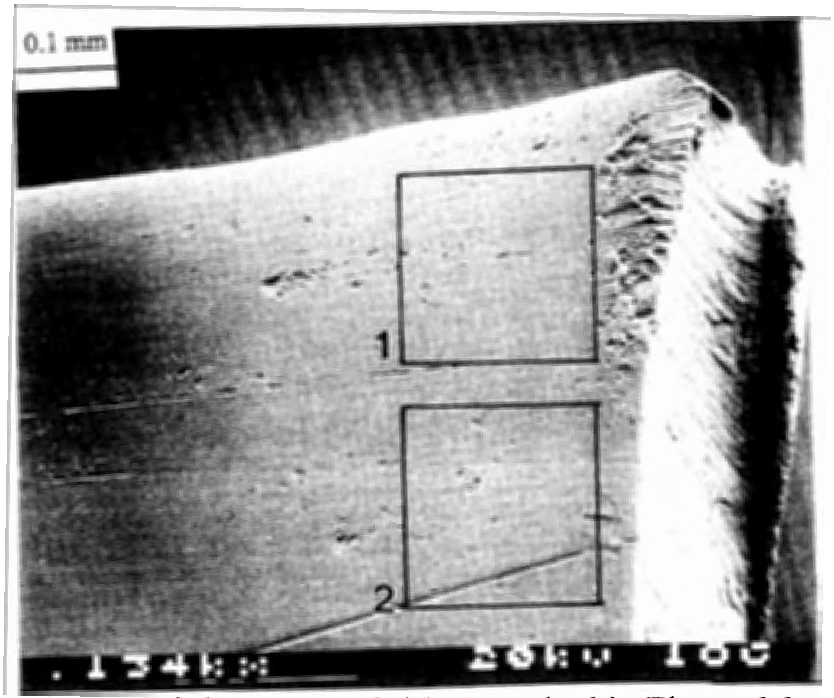


Figure 37. Upper right corner of side 2 marked in Figure 36. (wd 10 mm, tilt 45°, mag. 134x)

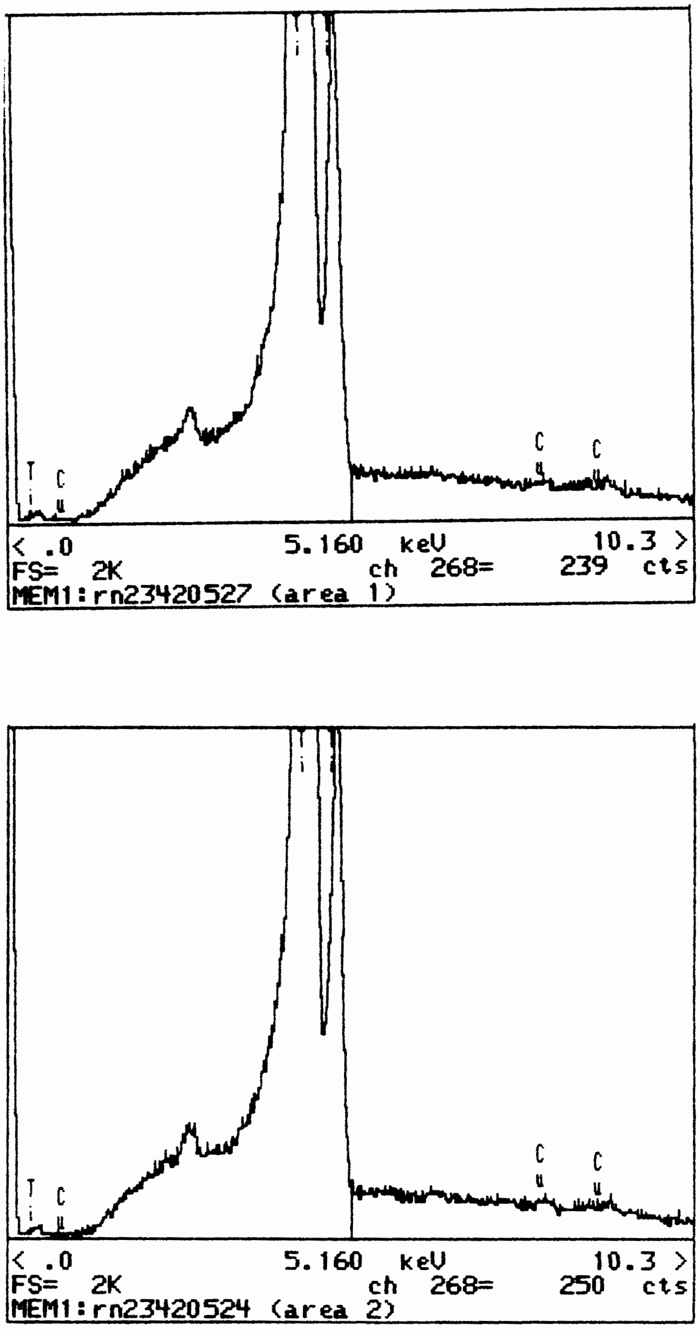


Figure 38. EDS spectra of areas marked in Figure 37.

Analyses after electrolysis of the titanium cathode for 50.5 hours (more than 2 times longer that in the first experiment):

After electrolysis the cathode was ultrasonically cleaned in deionised water bath several times, five minutes each time. This cleaning was possible, because the electrolyte did not attack the cathode as strongly as in the first experiment.

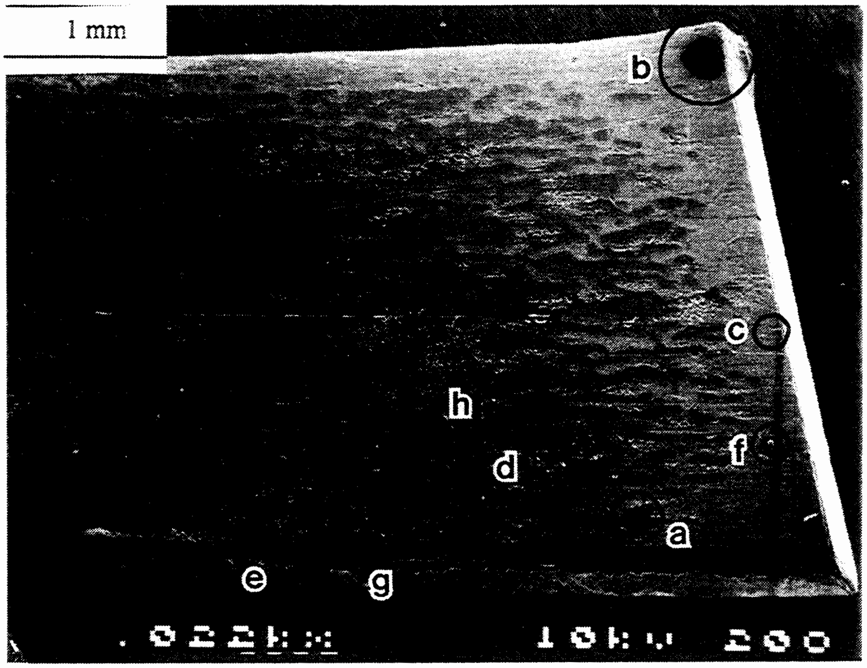


Figure 39. Side 2 after electrolysis (same area and mag. as in Figure 36). (wd 38, tilt 45°, mag. 19x)

The areas marked in Figure 39. (a-g) are examined more precisely in the following.

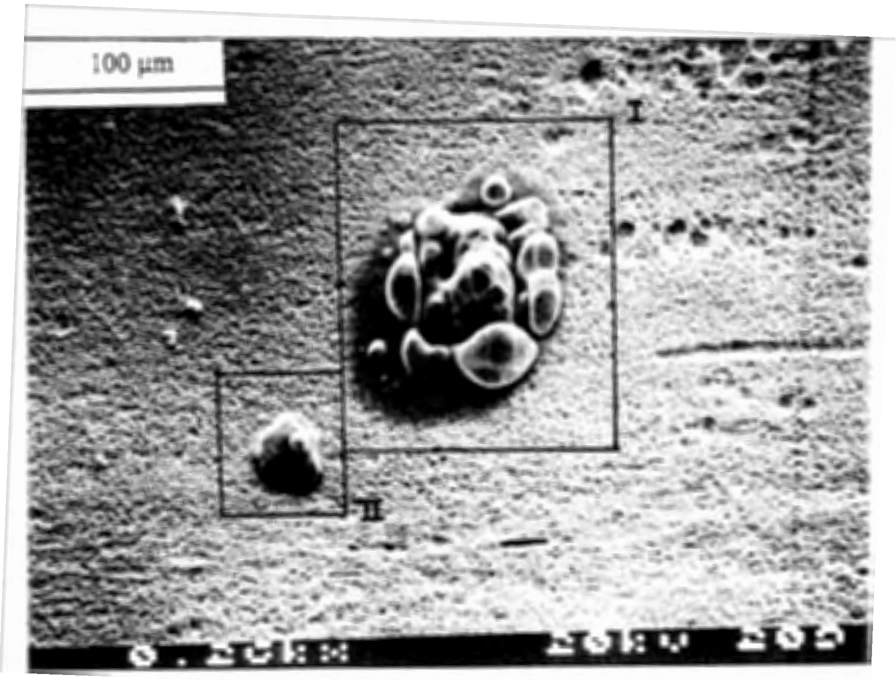


Figure 40. Region (a) from Figure 39.
(wd 10 mm, tilt 45°, mag. 260)

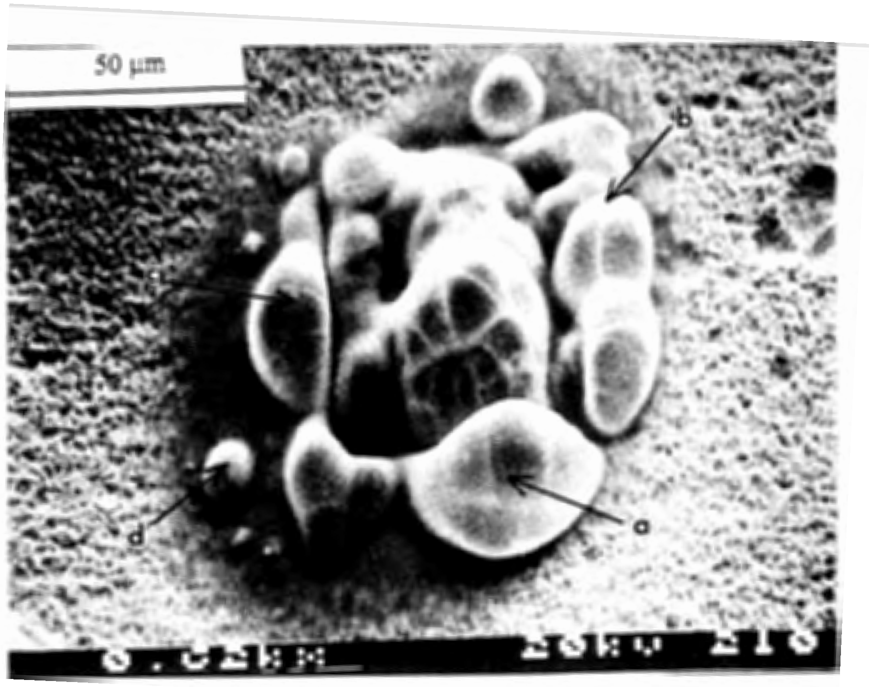


Figure 41. Higher magnification of area (a) (Region I from Figure 40). (wd 10 mm, tilt 45°, mag. 620)

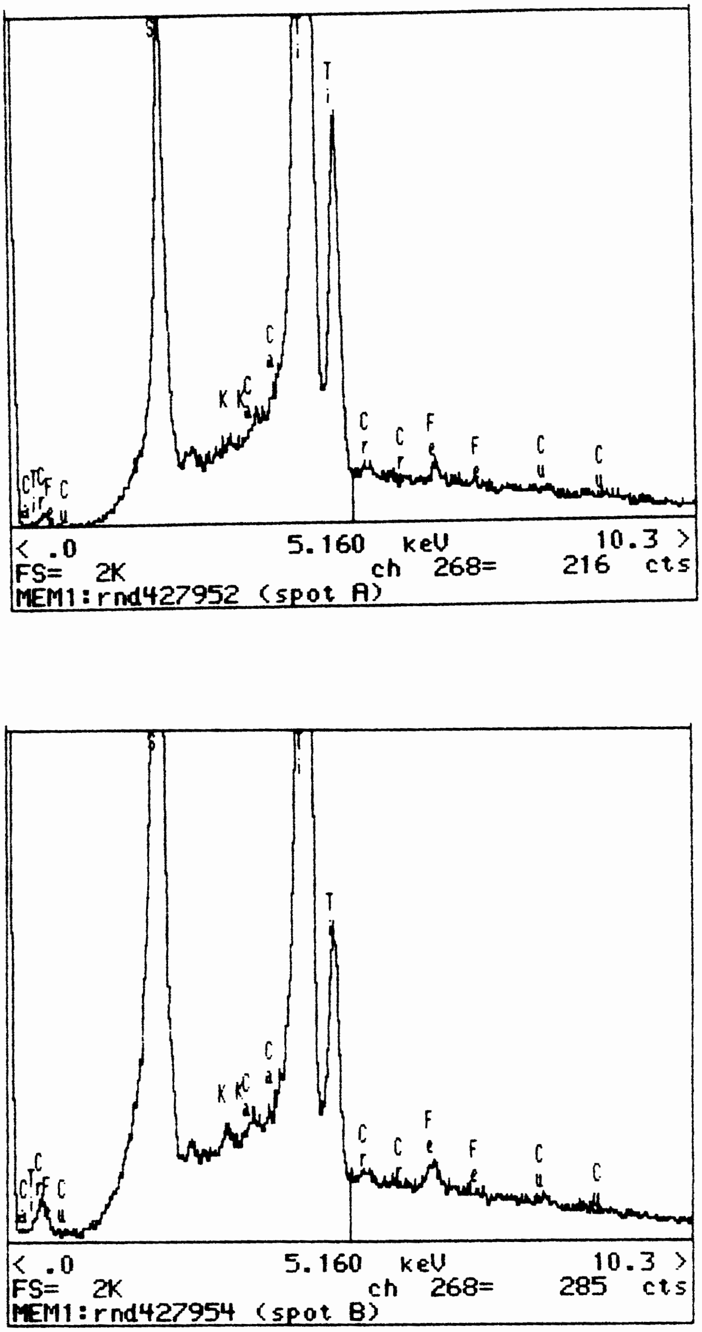
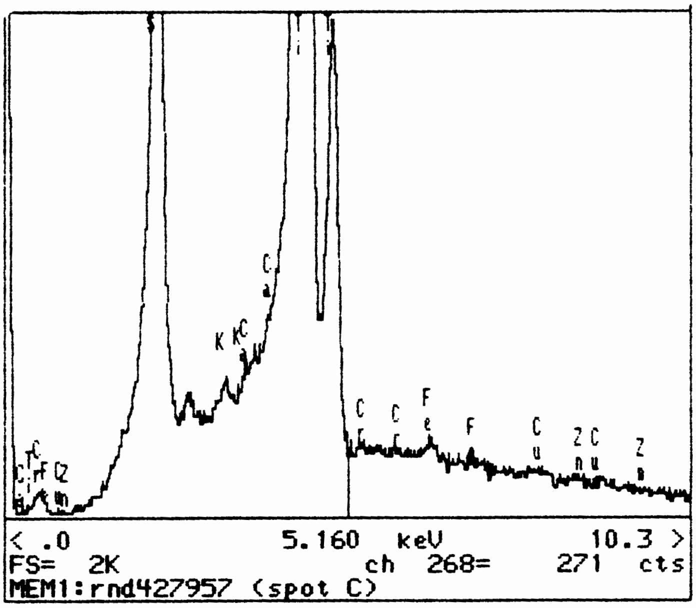
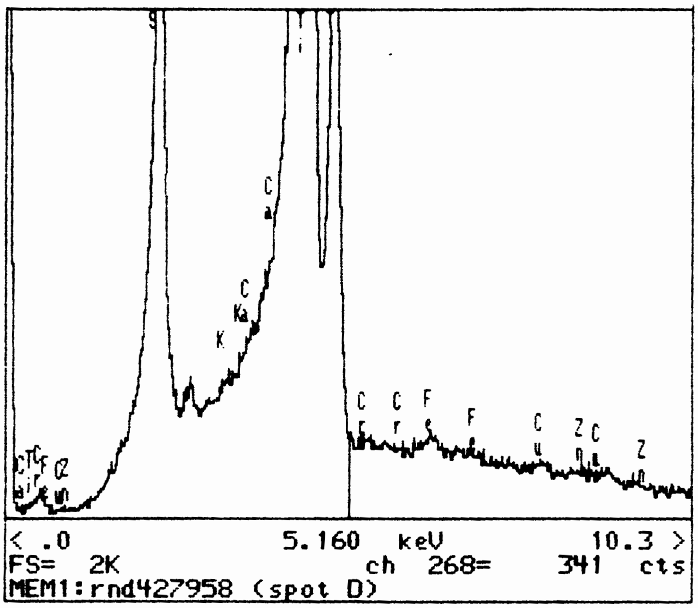


Figure 42. EDS spectra of spots marked in Figure 41.



```
< .0                5.160   keV          10.3 >
FS=  2K                  ch   268=      271   cts
MEM1:rnd427957 (spot C)
```



```
< .0                5.160   keV          10.3 >
FS=  2K                  ch   268=      341   cts
MEM1:rnd427958 (spot D)
```

Figure 42. EDS spectra of spots marked in Figure 41. (continued)

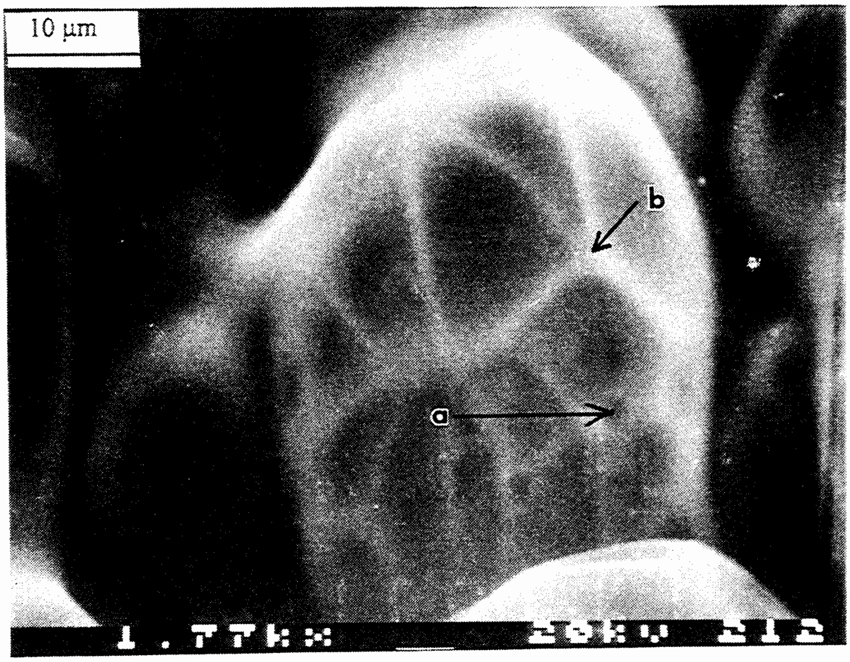


Figure 43. Higher magnification of Figure 41.
(wd 10 mm, tilt 45°, mag. 1770x)

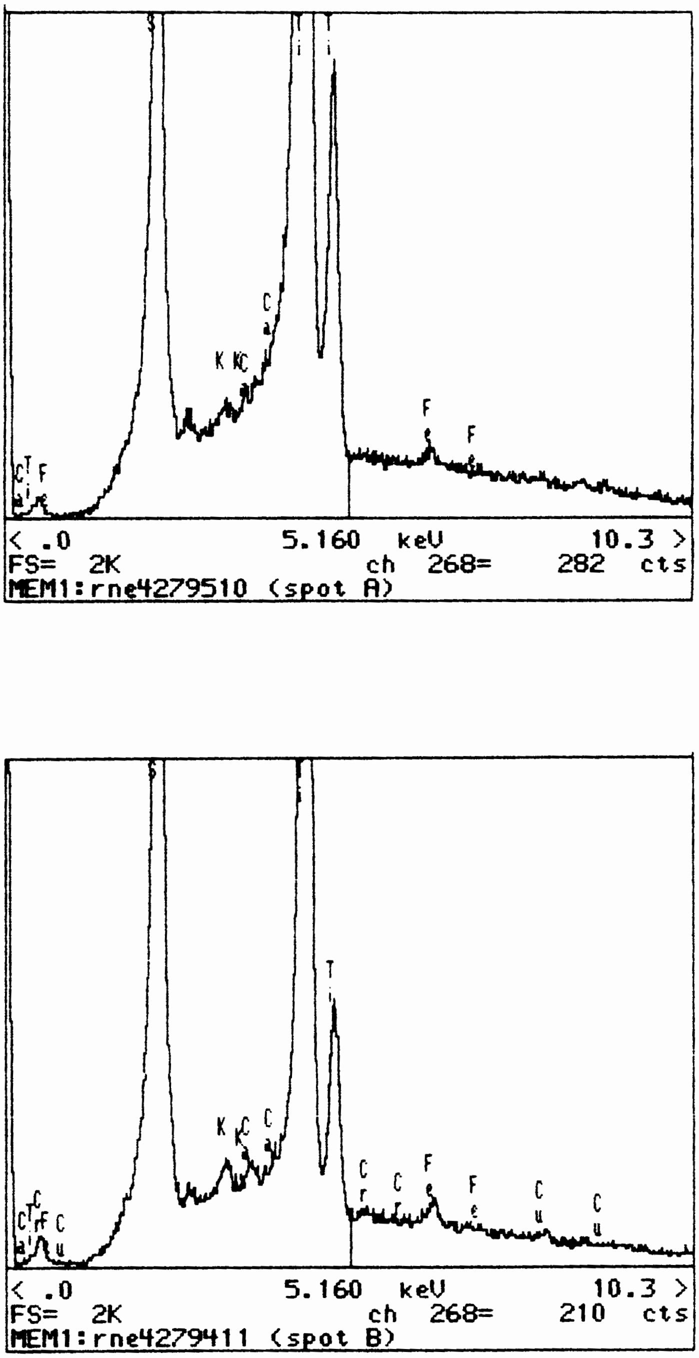


Figure 44. EDS spectra of spots marked in Figure 43.

The new elements which can be found in these regions after electrolysis are Zn and Cr. Zn has been already found in the first experiment but Cr is a new finding.

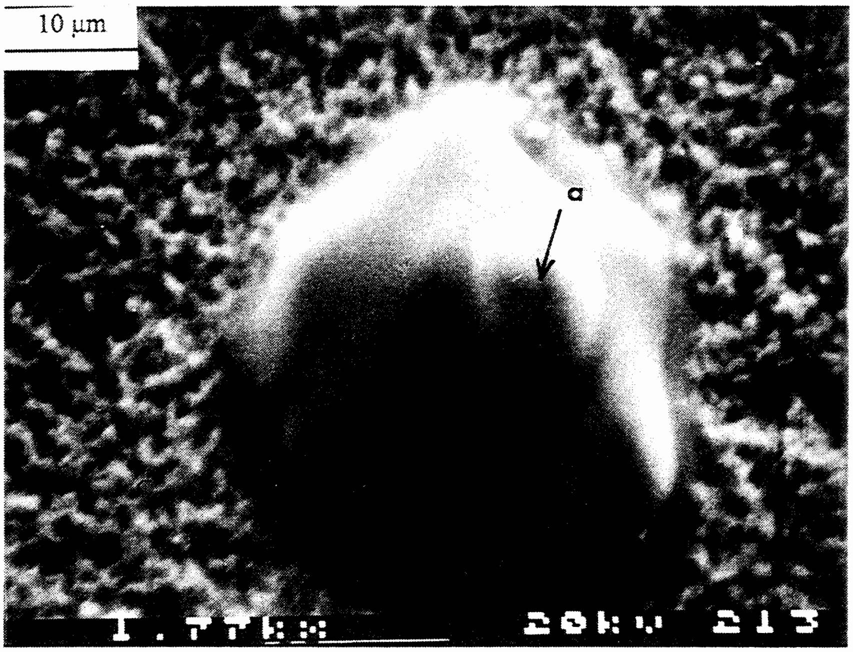


Figure 45. Higher magnification of Figure 40. (Region II)
(wd 10 mm, tilt 45°, mag. 1770x)

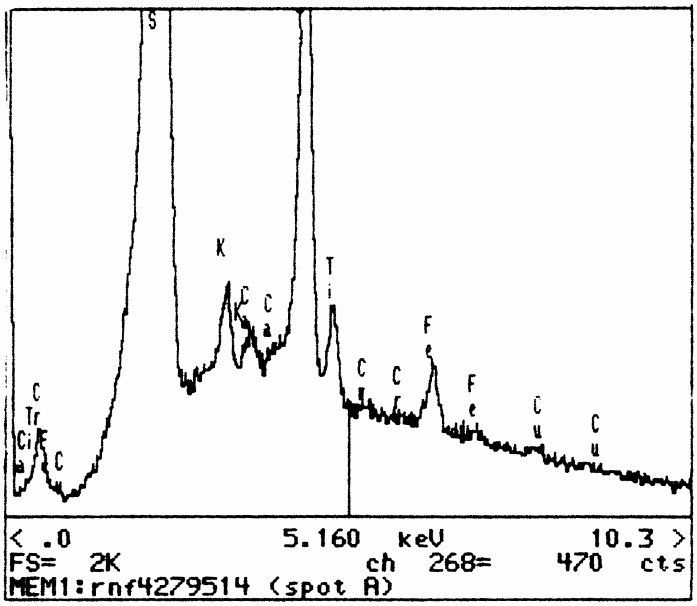


Figure 46. EDS spectrum of spot labeled in Figure 45.

K and Ca have very strong peeks in this region. Also Cr can be located.

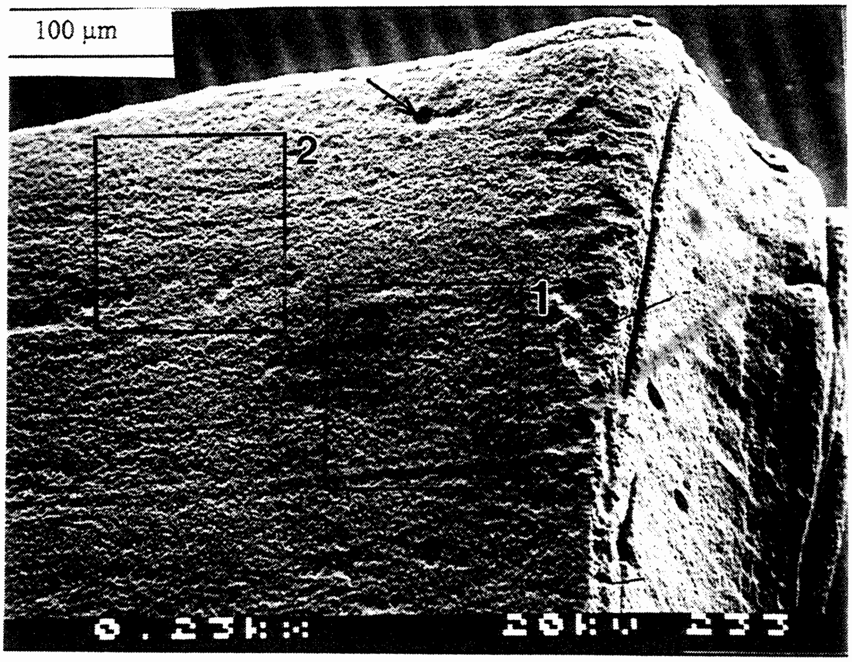


Figure 47. Area (b) marked in Figure 39.
(wd 10, tilt 45°, mag. 230x)

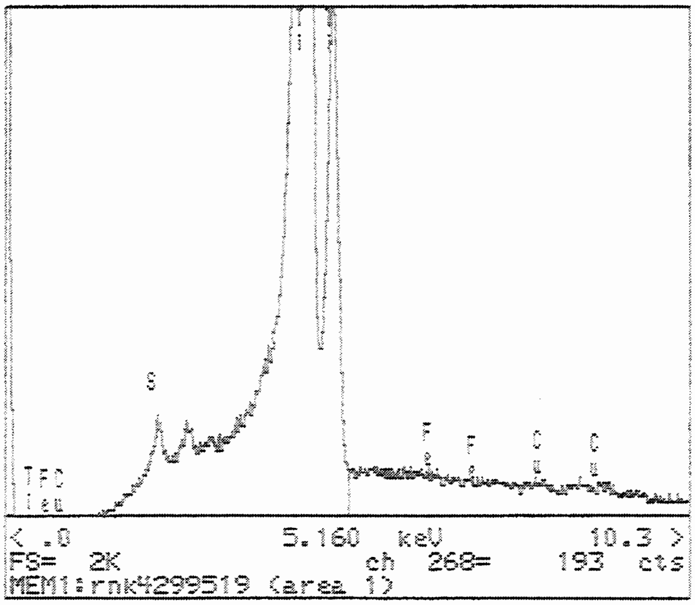
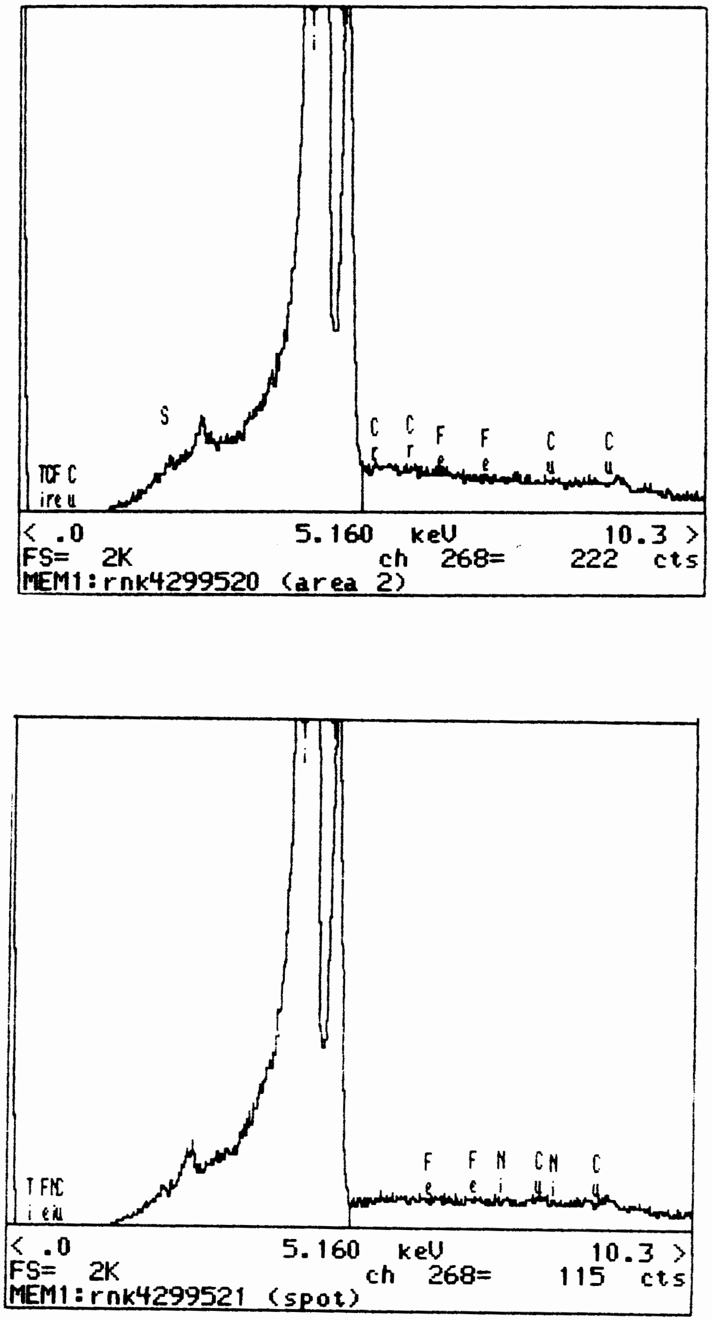


Figure 48. EDS spectrum of region marked in Figure 47.



```
< .0              5.160   keV           10.3 >
FS=   2K                  ch   268=      222   cts
MEM1:rnk4299520  (area 2)
```

```
< .0              5.160   keV           10.3 >
FS=   2K                  ch   268=      115   cts
MEM1:rnk4299521  (spot)
```

Figure 48. EDS spectra of regions marked in Figure 47. (continued)

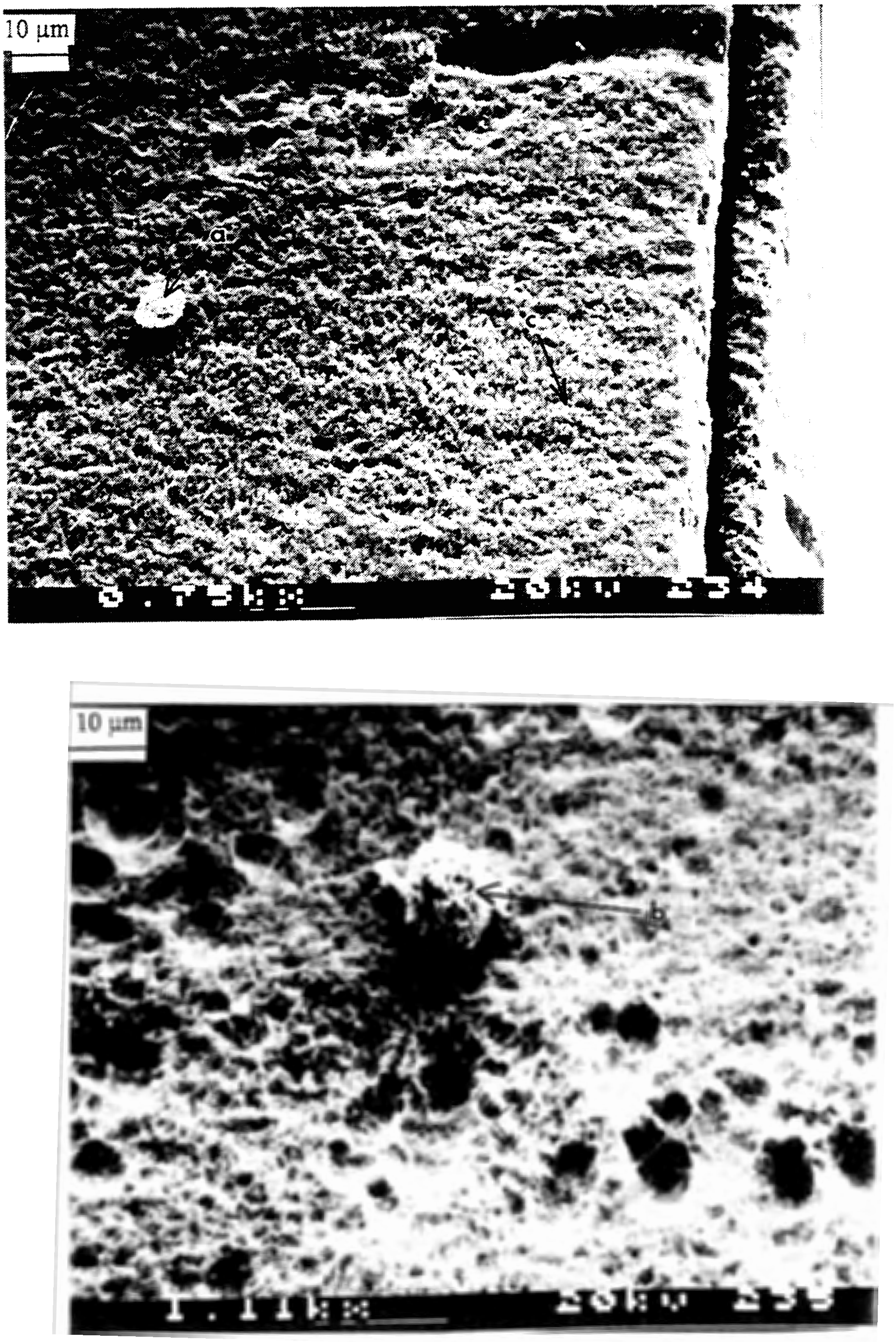


Figure 49. Areas (c) and (d) from Figure 39.
(wd 10 mm, tilt 45°, mag. 750x and 1110x)

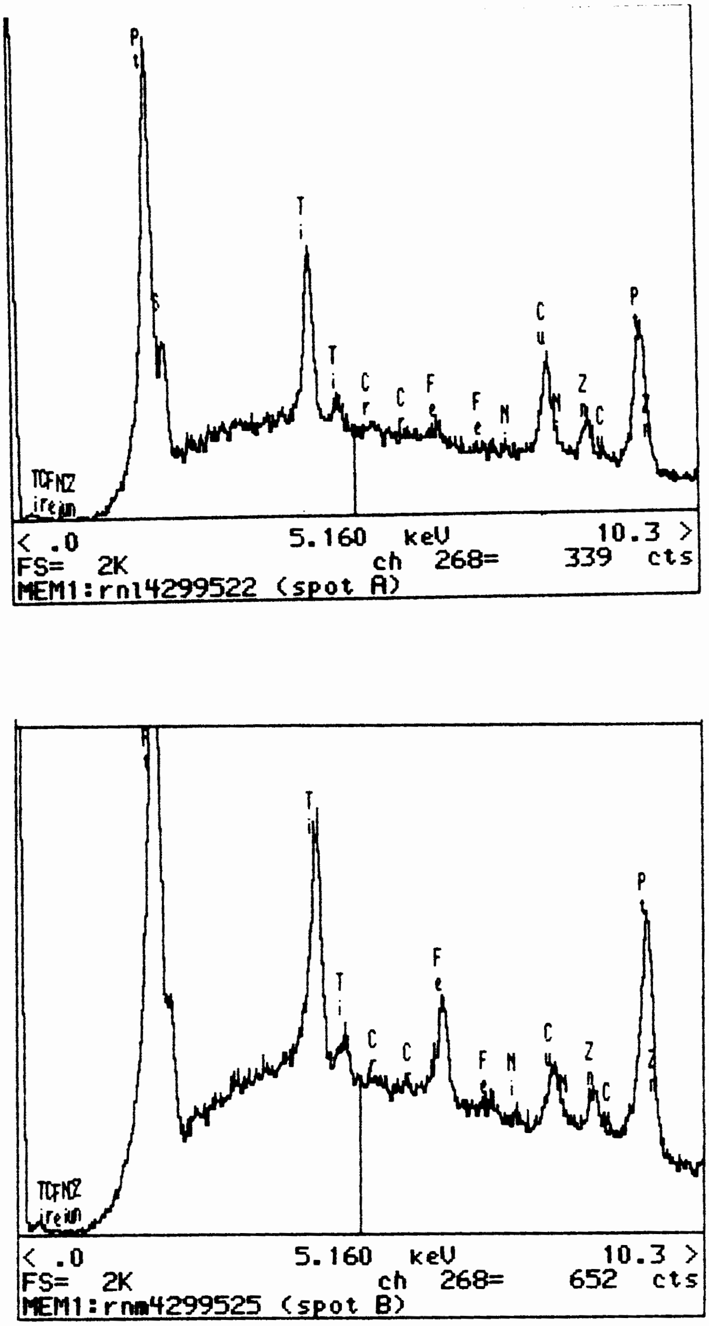


Figure 50. EDS spectra of spots marked in Figure 49.

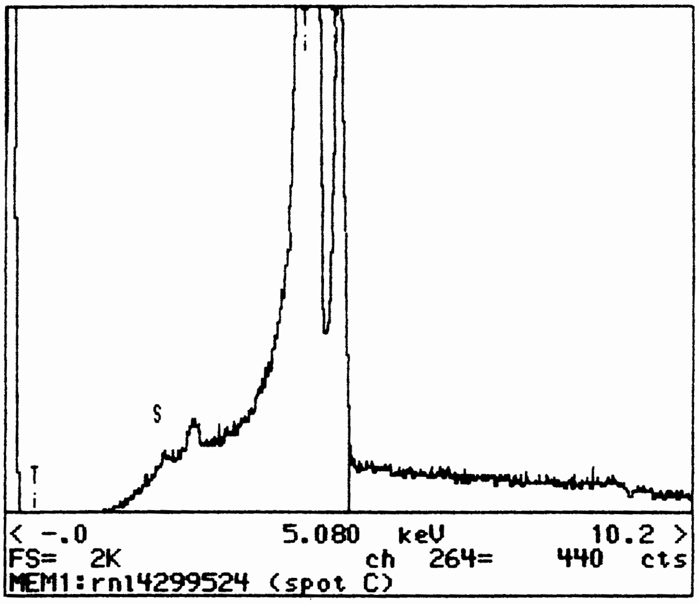


Figure 50. EDS spectrum of spot marked in Figure 49. (continued)

The Pt originated from the anode. The titanium cathode got covered by platinum. There are many similar "balls" all over the cathode. What is very surprising is the strong Zn and Cr peak. Also Ni can be located in this area.

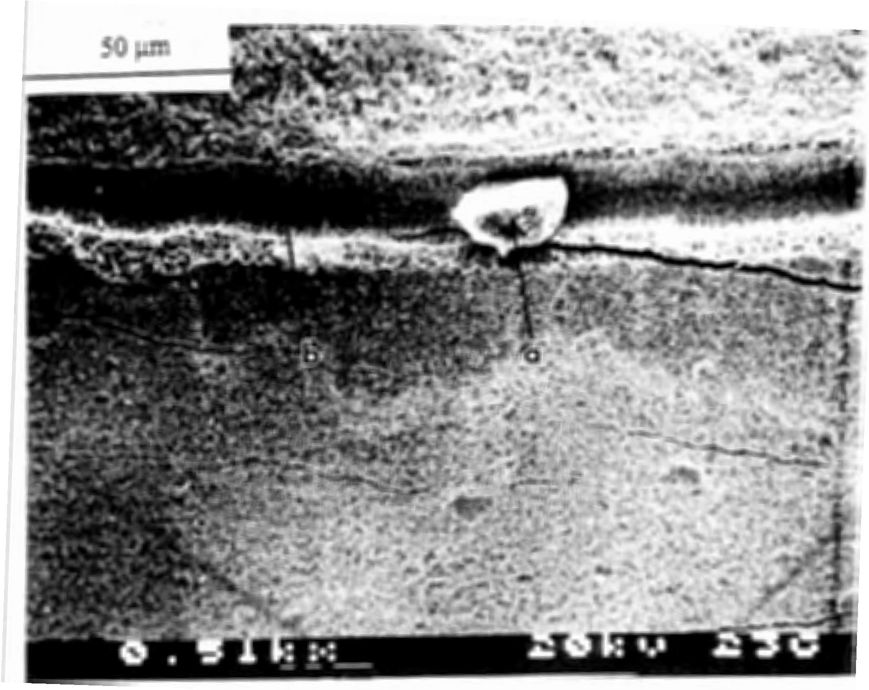


Figure 51. Area (e) from Figure 39.
(wd 10 mm, tilt 45°, mag. 510x)

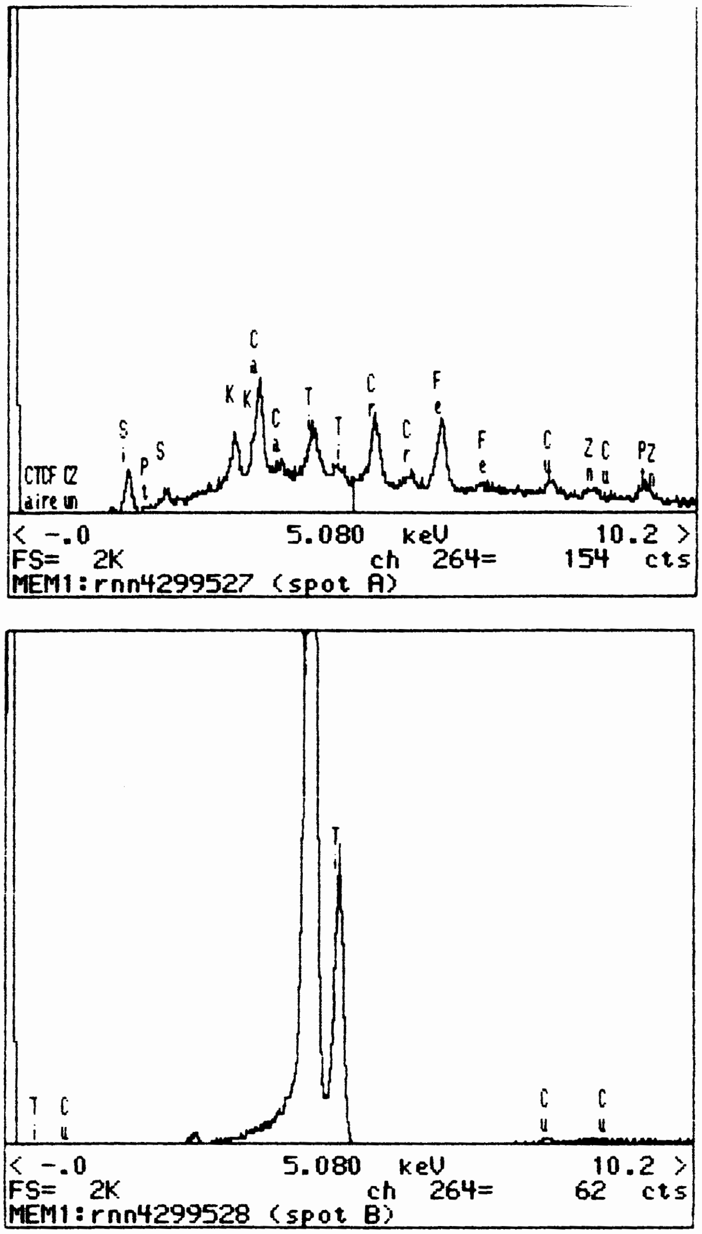


Figure 52. EDS spectra of spots marked in Figure 51.

The strongest Cr peak can be found in this area. Ca and K, Zn and Cu are present again.

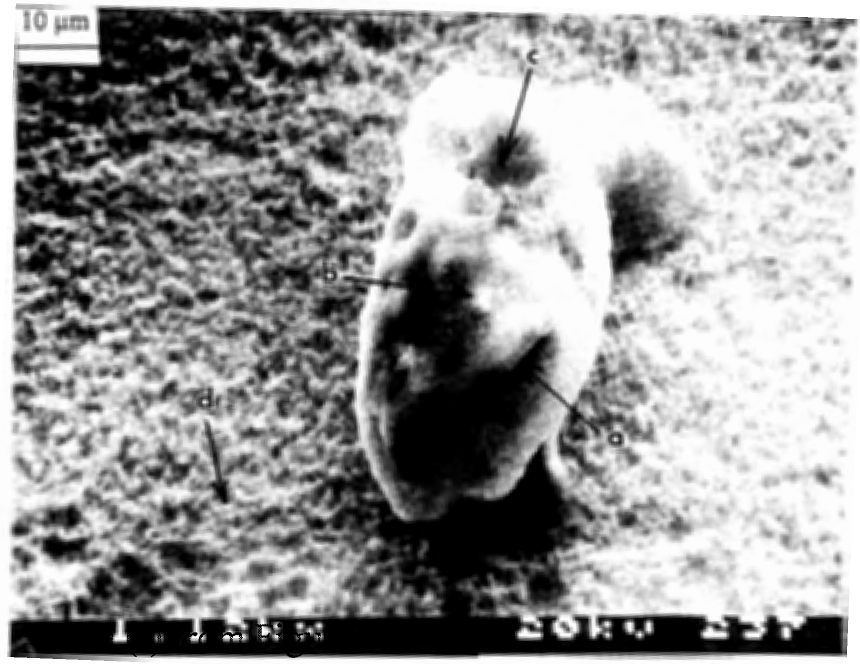


Figure 53.
(wd 10 mm, tilt 45°, mag. 1120x)

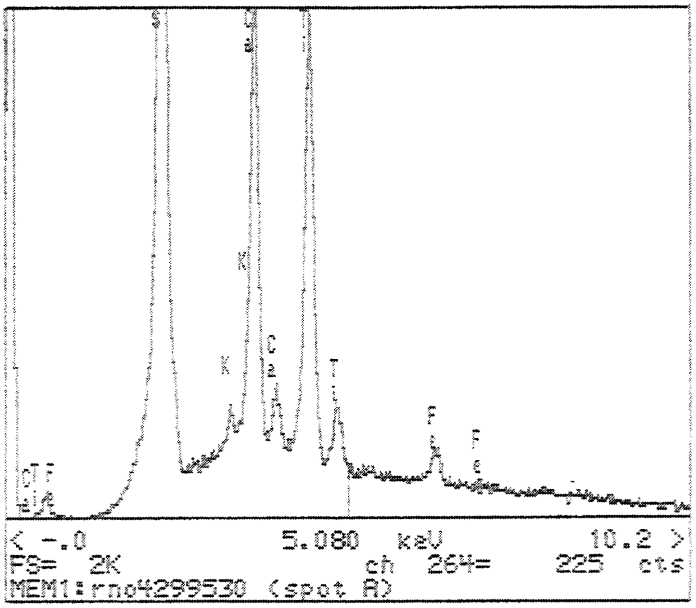


Figure 54. EDS spectrum of spot marked in Figure 53.

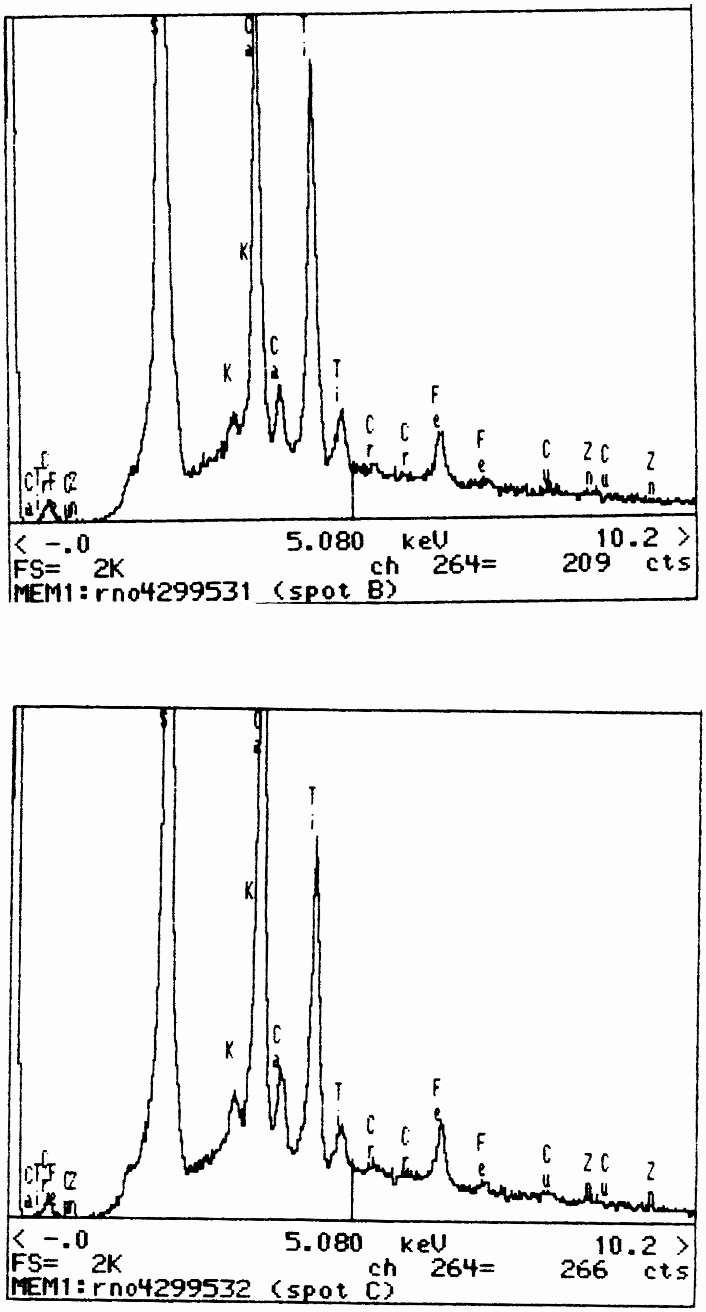


Figure 54. EDS spectra of spots marked in Figure 53. (continued)

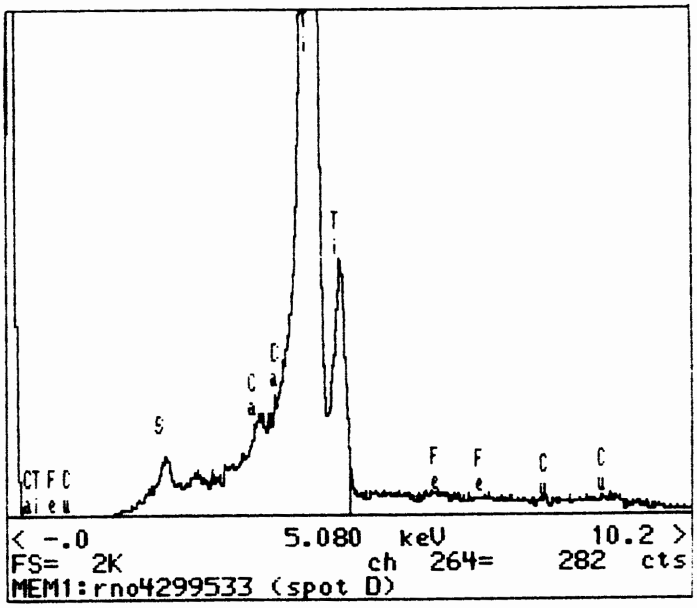


Figure 54. EDS spectrum of spot marked in Figure 53.

The same elements occur in this region again. Only the strength of the peaks is different. K and Ca are the strongest in this area.

Figure 55. Area (g) from Figure [illegible].
(wd 10 mm, tilt 45°, mag. 1100x)

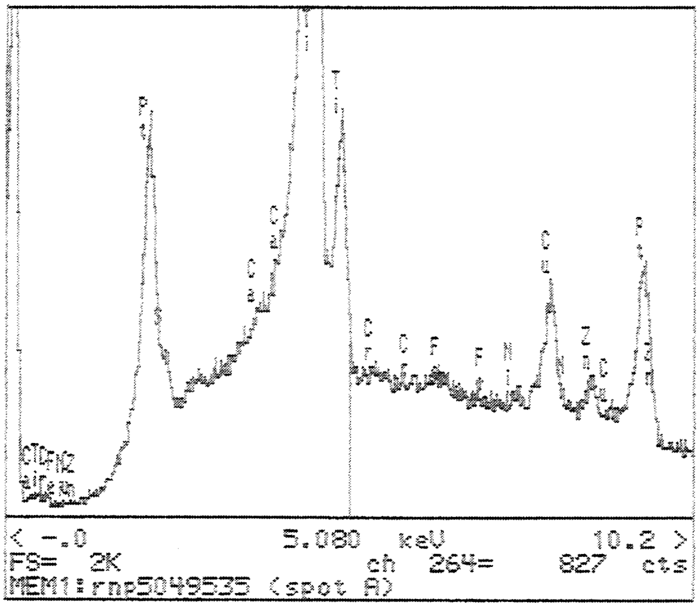


Figure 56. EDS spectrum of spot marked in Figure 55.

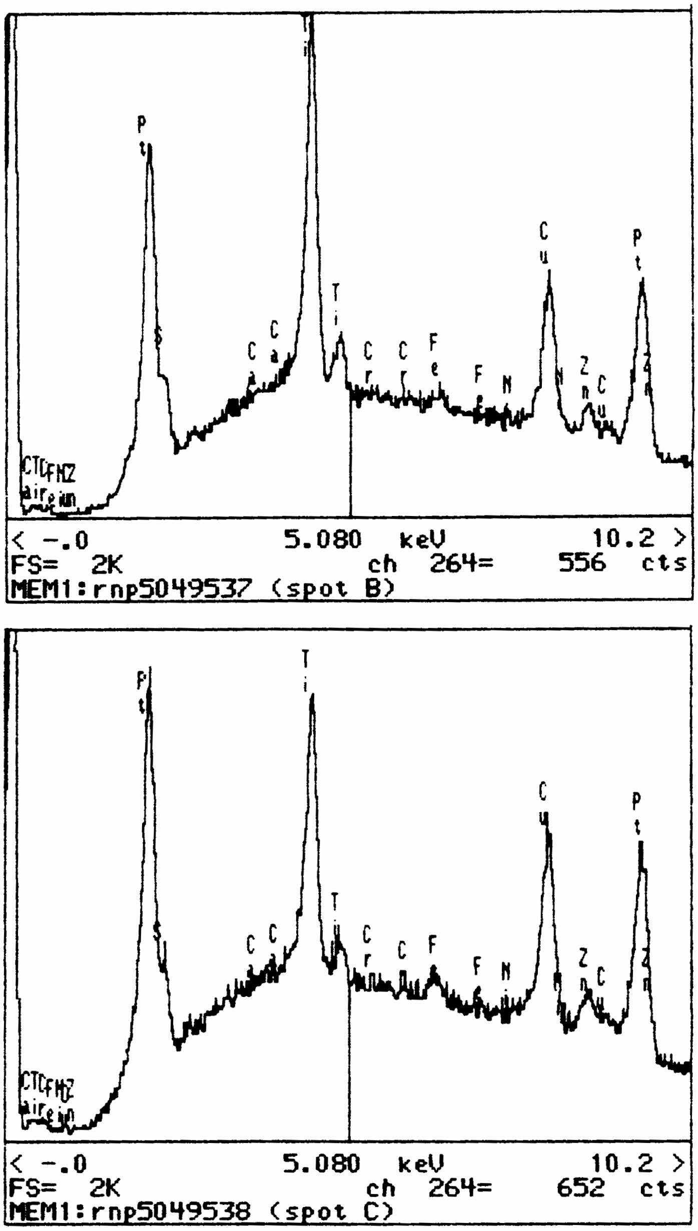


Figure 56. EDS spectra of spots marked in Figure 55. (continued)

The Cu-Zn “pair” has the strongest peak in this area. Cr is also present.

Figure 57. Area (h) from Figure 39.
(wd 10 mm, tilt 45°, mag. 3700x)

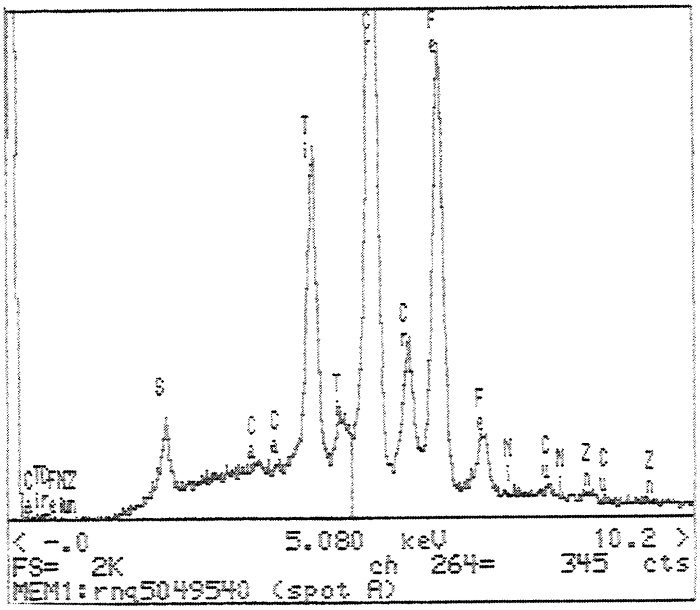


Figure 58. EDS spectrum of spot marked in Figure 57.

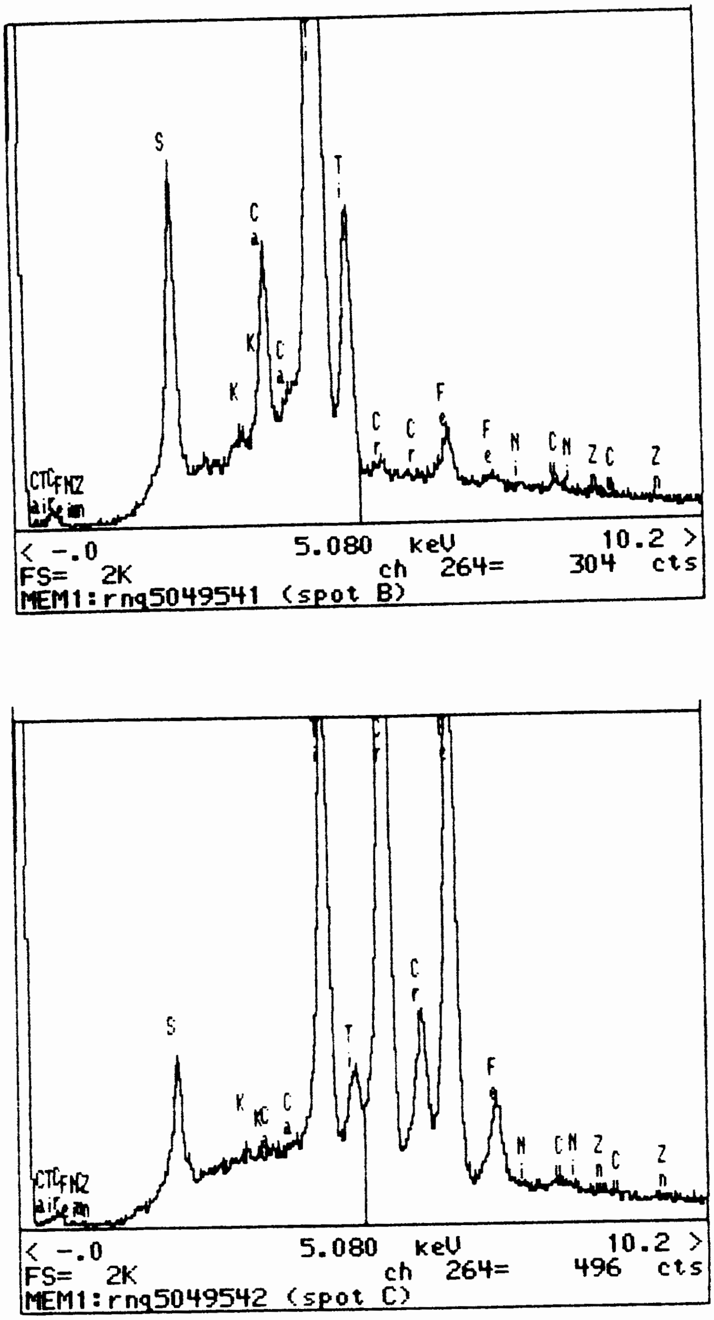


Figure 58. EDS spectra of spots marked in Figure 57. (continued)

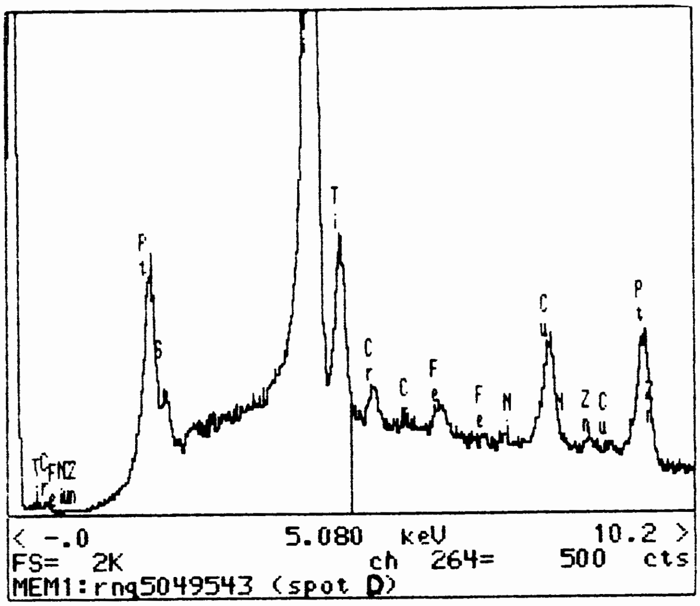


Figure 58. EDS spectrum of spot marked in Figure 57.

Cr and Fe peaks are very strong in this area. They are even stronger than the Ti peak.

The Cr, Fe, Ni, Zn and K impurities listed in the analysis provided by the supplier of the Ti cathode material would be an obvious source for these elements which are detected in EDS analysis. The cathode was made from 99.99+% pure titanium (Johnson Matthey, stock#: 13975, lot#: G07D10). The chemical analysis of the titanium can be found in the appendix.

The concentrations of the elements in question in the titanium before electrolysis (in ppm) were:

Fe	6.600
Cr	1.150
Ni	0.060
Zn	<0.035
K	<0.030

Table 6. Concentrations of some impurities in the titanium cathode before electrolysis.

As iron and chromium show the highest contaminations, some calculations will be done with these two elements. The assumption is that these elements occur homogeneously throughout the titanium before electrolysis.

The volume of the titanium cathode in the second experiment amounted to 0.0034 cm^3 (with 0.25mm thickness). The ratio of the Fe atoms to the Ti atoms in the cathode is 1 Fe/ $1.52*10^5$ Ti and of the Cr atoms 1 Cr/ $8.70*10^5$ Ti.

Mass density of ^{22}Ti: 4.51 g/cm^3 (atomic weight: 47.90)
^{26}Fe: 7.87 g/cm^3 (atomic weight: 55.85)
^{24}Cr: 8.96 g/cm^3 (atomic weight: 52.01)

⇒ Volume for one mol ^{22}Ti: $V_{mole} = (47.90/4.51)\ \mathrm{cm}^3 = 10.62\ \mathrm{cm}^3$
^{26}Fe: $V_{mole} = 7.10\ \mathrm{cm}^3$
^{24}Cr: $V_{mole} = 5.81\ \mathrm{cm}^3$

⇒ Volume for one atom ^{22}Ti: $V_{atom} = (10.62/6.023*10^{23})\ \mathrm{cm}^3$
$= \underline{1.76*10^{-23}\ \mathrm{cm}^3}$
^{26}Fe: $V_{atom} = \underline{1.18*10^{-23}\ \mathrm{cm}^3}$
^{24}Cr: $V_{atom} = \underline{0.96*10^{-23}\ \mathrm{cm}^3}$

Now the number of atoms for each element can be calculated.

$\Rightarrow X*1.76*10^{-23}\ \text{cm}^3+Y*1.18*10^{-23}\ \text{cm}^3+Z*0.96*10^{-23}\ \text{cm}^3 = 0.0034\ \text{cm}^3$

with $Y=X/1.52*10^5$ and $Z=X/8.70*10^5$

(X, Y, Z are the number of atoms)

Substitute and solve for X, Y and Z.

$\Rightarrow X = \underline{1.93*10^{20}}$(Ti atoms) , $Y = \underline{1.27*10^{15}}$ (Fe) , $Z = \underline{2.22*10^{14}}$ (Cr)

Out of this information the volume of each element included in the cathode can be calculated:

-The volume of Ti in the cathode is:

$1.93*10^{20} * 1.76*10^{-23}\ \text{cm}^3 = 0.0034\ \text{cm}^3$

This volume was expected because of the negligible contaminations.

-The volume of Fe in the cathode is:

$1.27*10^{15} * 1.18*10^{-23}\ \text{cm}^3 = \underline{\underline{1.50*10^{-8}\ \text{cm}^3}}$

This would be a cube with side length of 25 μm.

-The volume of Cr in the cathode is :

$2.22*10^{14} * 0.96*10^{-23}\ \text{cm}^3 = \underline{\underline{2.13*10^{-8}\ \text{cm}^3}}$

This would be a cube with side length of 28 μm.

The chromium cube is larger because of smaller mass density of Cr.

The electron beam for the EDS will penetrate about 1 μm. The volume of the cathode that emits x-rays when the beam is on a spot is roughly spherical:

$$4/3\ \pi*(1*10^{-4}\ \mathrm{cm}/2)^3 = \underline{5.2*10^{-13}\ \mathrm{cm}^3}$$

If all of the Fe was concentrated in a single area on the surface, then 100% concentration of Fe in the volume that x-ray luminescence would be a $(122*122)\mu m^2$ area. Chromium would be about $(146*146)\mu m^2$. An estimation calculation can be done if the amount of unexpected elements found on the cathode after the electrolysis increased. It is very hard to say, because Fe and Cr are not miscible in Ti in the temperatures used, i.e. they can occur as clusters. A more precise method as the SEM would be needed for this purpose.

Results from the second experiment

Excess heat was observed in the D cell in comparison to the C cell during the whole measurements for 33 hours. A calculation for the first 20 minutes underlines this result on page 47.

A small difference in radiation collection was detected in both cells, the D cell being higher. But the standard deviation is too high to have confidence in this data. For the TLD chips the time was still too short to have any significant readings out of the chips. The same experiment should be repeated for a longer time, at least for one week. For this reason the concentration of the H_2SO_4 in the electrolyte should be lowered again and the amount of electrolyte should be increased. This means other cells must be constructed with a bigger volume.

During the morphology and microanalysis of the Ti cathode the elements found in the first experiment occurred again on the surface of the cathode but also new elements have been found (old: Zn, Ni and Fe). The new unexpected elements are Cr, Ca and K.

RESULTS

No significant emission of any of the products associable with deuterium-deuterium fusion was observed. The readings out of the TL chips were under the threshold of significance, and the standard deviation for the emission of the radiation collected by the GM-tubes was too high.

In the second experiment a large amount of excess heat was found for the D cell in comparison to the control.

Highly localized, unexpected elements were found in both experiments. Zn, Ni and Fe were found in both experiments, Cr, K and Ca only in the second experiment.

CONCLUSION

It appears that excess heat is produced during electrolyses of heavy water with a titanium cathode. The amount of this excess heat seems comparable to that produced with a palladium cathode(3).

No significant emission of any of the products associated with a "classical" deuterium-deuterium fusion was observed during both experiments, i.e. heat but no radiation.

Unexpected elements were found in both experiments. Remarkable is the fact that the new elements always occur very close in the periodic table to an impurity element, i.e. Zn with Cu.

impurity	new element
Cu	Zn
Ca	K
‘Ti’	Cr

Table 6. New elements found on the Ti cathode after electrolysis

It is not clear if Fe is detected due to contamination or if it is also a new element in higher concentration. If the first is the case then Fe-Ni would be an additional “pair”. Although occurring in only a small fraction of the titanium cathode, these unexpected elements correlate with measured excess heat and may have arisen through transmutation caused by neutrons from nuclear fusion reaction. It is possible that the impurity elements (Cu, Ca, “Ti”) capture the neutrons produced by the possible deuteron-deuteron fusion and decay to the elements next to them. But then e^- or e^+ should be detected by the GM counters.

Possible reaction[11)]:

$$^{64}\mathrm{Cu} \xrightarrow{12.701\ \mathrm{h}} {}^{64}\mathrm{Ni} + e^{-}$$

But as mentioned above, some radiation should then be detected.

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TABLES AND APPENDIX

Radiation data from the D and C cell

	EXPERIMENT				BACKGROUND			
time [h]	countrate D-cell	st.dev. D-cell	countrate C-cell	st.dev. C-cell	countrate D-cell(ba)	st.dev. D-cell	countrate C-cell(ba)	st.dev. C-cell
1	695	6	619	6	605	6	627	5
2	685	6	598	6	569	6	649	4
3	631	7	573	6	615	5	632	6
4	672	6	634	6	670	5	574	5
5	642	7	657	4	614	6	607	4
6	606	6	598	6	577	6	588	6
7	632	5	579	5	588	7	602	5
8	664	3	607	5	649	7	583	5
9	666	6	595	5	637	6	603	5
10	602	5	588	6	644	5	633	5
11	668	6	664	6	601	6	594	6
12	623	5	675	6	624	5	592	4
13	647	8	622	5	678	7	586	5
14	639	5	606	7	574	5	564	5
15	595	5	608	4	628	7	577	6
16	646	6	633	6	646	5	603	7
17	653	5	586	6	562	6	680	5
18	578	5	620	7	667	6	606	6
19	653	6	554	5	635	4	580	5
20	626	7	675	6	616	6	583	4
21	628	7	628	6	593	5	551	5
22	636	7	622	7	620	6	614	5
23	638	6	624	6	634	6	625	7
24	642	7	616	6	623	5	571	6
25	628	6	591	4	573	6	514	5
26	666	6	600	6	616	6	624	5
27	658	6	600	4	585	6	597	6
28	640	7	627	4	623	6	605	8
29	663	6	594	5	609	7	570	6
30	620	5	597	5	599	7	615	5
31	658	4	582	6	593	6	595	6
32	599	6	636	5	599	6	575	6
33	645	8	577	5	652	6	591	4
34	671	7	654	7	608	7	583	5
35	632	7	621	5	662	6	603	4
36	655	5	588	5	628	7	621	5
37	653	7	590	5	564	6	594	7
38	638	5	612	5	616	5	617	6
39	657	5	651	8	610	6	589	6
40	636	6	657	5	604	6	548	6

41	656	6	629	6		598	6	598	6
42	682	7	688	6		606	7	586	5
43	607	5	579	6		582	5	624	4
44	629	5	600	5		622	5	583	5
45	602	6	596	5		617	6	593	5
46	609	7	668	5					
47	661	6	655	7	average b.	614		597	
48	574	7	664	5	st. dev. b.	28		28	
49	674	6	615	5					
50	642	6	618	6					
51	619	6	649	5					
52	665	6	663	6					
53	618	5	582	6					
54	635	6	633	6					
55	658	7	543	4					
56	591	5	584	6					
57	636	5	582	4					
58	611	5	632	5					
59	662	5	602	6					
60	640	5	597	5					
61	628	5	663	4					
62	719	6	615	4					
63	645	5	642	4					
average	640		617						
st. dev.	28		32						

Experiment 2

comparison in temperature and power input for D and C cell

(in 30 minutes intervalls)

time[min]	average temp D[C]	standard deviation	average temp C[C]	standard deviation	voltage[V] D-cell	[VAs] energy D	[W] power D	voltage[V] C-cell	[VAs] energy C	[W] power C
0	23.7	0.3	23.9	0.8	0.0	0.0	0.0	0.0	0.0	0.0
30	42.8	3.4	38.5	3.8	4.1	4092.0	2.3	5.0	4947.6	2.7
60	44.7	3.5	40.8	4.4	4.0	4002.5	2.2	4.9	4836.4	2.7
90	43.8	2.5	40.7	4.1	4.0	3917.9	2.2	4.9	4858.2	2.7
120	43.0	2.7	40.6	5.1	4.0	4005.0	2.2	5.0	4947.6	2.7
150	42.8	3.0	40.2	4.5	4.0	3951.8	2.2	4.8	4734.9	2.6
180	42.9	2.8	39.8	5.1	4.0	3990.5	2.2	5.0	4904.1	2.7
210	42.3	2.7	39.6	4.5	4.0	3959.0	2.2	5.0	4937.9	2.7
240	41.7	2.6	39.6	4.3	4.0	4007.3	2.2	5.0	4947.6	2.7
270	41.8	2.8	39.6	4.5	4.0	3983.2	2.2	4.9	4841.2	2.7
300	41.8	2.8	39.9	4.9	4.1	4043.6	2.2	4.9	4838.8	2.7
330	42.3	3.7	39.6	4.9	3.9	3886.5	2.2	4.7	4693.8	2.6
360	42.3	2.9	39.6	4.8	4.0	3956.6	2.2	4.6	4543.9	2.5
390	43.6	3.3	40.1	5.8	3.9	3885.1	2.2	4.8	4744.6	2.6
420	43.0	2.9	39.8	5.0	4.1	4055.7	2.3	4.8	4742.1	2.6
450	43.5	3.2	40.2	6.2	4.0	3932.4	2.2	4.6	4587.5	2.5
480	43.1	2.8	40.8	5.7	4.0	3988.0	2.2	4.5	4498.0	2.5
510	43.9	3.7	40.1	5.5	4.0	3934.9	2.2	4.8	4720.4	2.6
540	43.8	3.5	40.3	6.3	4.0	3956.6	2.2	4.8	4708.3	2.6
570	43.7	3.7	37.7	5.8	3.9	3876.9	2.2	4.7	4657.5	2.6
600	43.6	3.2	38.0	6.3	4.0	4005.0	2.2	4.6	4543.9	2.5
630	44.0	3.5	37.7	6.7	3.9	3903.4	2.2	4.5	4471.4	2.5
660	44.0	3.1	37.9	6.7	4.0	3954.2	2.2	4.3	4220.1	2.3
690	44.0	4.1	36.8	6.4	4.0	3954.2	2.2	4.5	4442.4	2.5
720	43.2	3.5	36.7	6.8	4.0	3966.3	2.2	4.5	4442.4	2.5
750	43.3	4.5	36.8	6.6	3.9	3898.6	2.2	4.5	4427.9	2.5
780	43.7	4.0	37.2	6.8	3.9	3884.1	2.2	4.5	4442.4	2.5
810	43.6	5.2	37.6	6.8	3.9	3903.4	2.2	4.6	4587.5	2.5
840	43.3	4.2	37.3	7.2	4.0	3990.5	2.2	4.6	4510.1	2.5
870	43.4	3.7	38.1	7.4	4.0	3930.0	2.2	4.6	4517.4	2.5
900	44.3	4.3	38.2	6.6	3.9	3893.8	2.2	4.4	4394.1	2.4
930	44.4	4.2	37.8	6.6	4.0	3971.1	2.2	4.4	4314.3	2.4
960	44.2	3.7	37.5	7.1	4.0	3910.7	2.2	4.5	4471.4	2.5
990	43.0	3.6	37.2	7.1	3.9	3891.4	2.2	4.3	4215.2	2.3
1020	43.3	4.3	37.3	7.1	3.9	3874.4	2.2	4.3	4227.3	2.3
1050	45.7	4.2	39.0	8.0	3.8	3794.7	2.1	4.3	4287.7	2.4
1080	45.5	3.9	37.9	7.4	3.9	3874.4	2.2	3.8	3765.7	2.1
1110	45.5	3.3	37.2	6.8	3.8	3789.8	2.1	3.8	3772.9	2.1

1140	45.9	3.8	37.2	7.3	3.8	3787.4	2.1	3.7	3669.0	2.0
1170	46.0	4.0	37.4	6.4	3.8	3765.7	2.1	3.7	3625.5	2.0
1200	45.6	3.9	37.5	7.2	3.9	3826.1	2.1	3.8	3799.5	2.1
1230	45.7	4.3	37.6	7.0	3.8	3734.3	2.1	3.8	3741.5	2.1
1260	45.4	4.6	37.4	6.7	3.8	3756.0	2.1	3.8	3736.7	2.1
1290	45.8	4.1	37.6	7.8	3.9	3816.4	2.1	3.6	3591.7	2.0
1320	46.5	4.1	38.4	7.1	3.8	3765.7	2.1	3.7	3671.4	2.0
1350	45.9	3.8	38.3	6.8	3.8	3743.9	2.1	3.7	3666.6	2.0
1380	47.0	5.4	38.6	7.4	3.8	3777.8	2.1	3.6	3545.7	2.0
1410	40.3	4.5	26.8	2.0	4.0	3922.8	2.2	0.0	0.0	0.0
1440	44.4	4.8	24.3	1.1	3.9	3843.0	2.1	0.0	0.0	0.0
1470	45.2	4.6	23.7	1.0	3.9	3821.3	2.1	0.0	0.0	0.0
1500	45.5	5.6	23.5	1.1	3.8	3787.4	2.1	0.0	0.0	0.0
1530	45.2	4.5	23.2	0.7	3.8	3739.1	2.1	0.0	0.0	0.0
1560	45.0	4.8	23.3	0.6	3.8	3780.2	2.1	0.0	0.0	0.0
1590	45.1	5.6	23.2	1.4	3.9	3828.5	2.1	0.0	0.0	0.0
1620	44.9	4.3	23.2	0.9	3.9	3816.4	2.1	0.0	0.0	0.0
1650	45.0	4.8	23.1	0.5	3.9	3838.2	2.1	0.0	0.0	0.0
1680	45.3	5.0	23.2	1.3	3.9	3823.7	2.1	0.0	0.0	0.0
1710	44.9	4.6	23.2	1.0	3.8	3787.4	2.1	0.0	0.0	0.0
1740	44.6	4.1	23.2	1.3	3.8	3801.9	2.1	0.0	0.0	0.0
1770	44.8	3.4	23.3	0.8	3.8	3724.6	2.1	0.0	0.0	0.0
1800	45.4	3.9	23.4	1.1	3.9	3830.9	2.1	0.0	0.0	0.0
1830	45.2	3.7	23.3	0.8	3.8	3777.8	2.1	0.0	0.0	0.0
1860	45.3	3.6	23.4	0.8	3.9	3855.1	2.1	0.0	0.0	0.0
1890	45.2	4.0	23.1	1.2	3.8	3787.4	2.1	0.0	0.0	0.0
1920	45.4	4.0	23.4	1.1	3.9	3872.0	2.2	0.0	0.0	0.0
1950	44.1	3.2	22.8	1.3	3.9	3814.0	2.1	0.0	0.0	0.0
1980	43.2	4.3	22.6	0.7	3.9	3840.6	2.1	0.0	0.0	0.0

comparison in temperature and power input for D and C cell

(beginning in 1 minute intervalls)

time[min]	average temp D[C]	standard deviation	average temp C[C]	standard deviation	voltage[V] D-cell	[VAs] energy D	[W=UI] power D	voltage[V] C-cell	[VAs] energy C	[W=UI] power C
0	23.7	0.3	23.9	0.8	0.0	0.0	0.0	0.0	0.0	0.0
1	25.0	2.0	24.4	0.9	4.7	155.9	2.6	5.0	164.9	2.7
2	26.4	2.8	25.5	1.4	4.7	154.7	2.6	5.0	164.9	2.7
3	27.8	3.4	26.6	1.6	4.6	151.0	2.5	5.0	164.9	2.7
4	28.9	3.3	27.4	2.2	4.5	149.3	2.5	5.0	164.9	2.7
5	30.2	3.2	28.6	2.6	4.5	149.5	2.5	5.0	164.9	2.7
6	31.5	2.9	29.4	2.4	4.6	151.5	2.5	5.0	164.9	2.7
7	32.5	2.6	30.2	2.2	4.5	149.9	2.5	5.0	164.9	2.7
8	33.4	2.8	31.0	2.6	4.3	140.6	2.3	5.0	164.9	2.7
9	34.4	2.7	31.9	2.5	4.3	140.9	2.3	5.0	164.9	2.7
10	35.1	2.8	32.4	3.0	4.3	140.7	2.3	5.0	164.9	2.7
11	35.9	2.8	33.1	3.2	4.3	140.7	2.3	5.0	164.9	2.7
12	36.8	2.9	33.9	3.4	4.2	139.1	2.3	5.0	164.9	2.7
13	37.5	2.6	34.4	3.1	4.2	140.2	2.3	5.0	164.9	2.7
14	38.0	2.6	35.0	3.5	4.2	137.7	2.3	5.0	164.9	2.7
15	38.7	2.9	35.5	3.9	4.2	138.7	2.3	5.0	164.9	2.7
16	39.2	3.0	35.8	3.8	4.3	140.3	2.3	5.0	164.9	2.7
17	39.8	2.9	36.4	3.8	4.2	137.6	2.3	5.0	164.9	2.7
18	39.7	3.2	35.9	3.7	4.2	138.6	2.3	5.0	164.9	2.7
19	39.9	3.3	36.0	3.3	4.3	140.7	2.3	5.0	164.9	2.7
20	40.3	3.3	36.4	3.7	4.2	138.2	2.3	5.0	164.9	2.7
21	40.7	3.5	36.7	3.4	4.1	136.9	2.3	5.0	164.9	2.7
22	40.9	3.6	36.9	3.5	4.2	137.0	2.3	5.0	164.9	2.7
23	41.3	3.6	37.1	3.4	4.2	137.7	2.3	5.0	164.9	2.7
24	41.2	3.2	37.4	3.7	4.2	139.1	2.3	5.0	164.9	2.7
25	41.2	3.9	37.8	3.3	4.3	140.7	2.3	5.0	164.9	2.7
26	42.0	4.2	37.9	4.0	4.2	140.2	2.3	5.0	164.9	2.7
27	42.2	3.4	38.1	4.3	4.2	139.5	2.3	5.0	164.9	2.7
28	42.3	4.3	38.2	4.1	4.2	139.1	2.3	5.0	164.9	2.7
29	42.7	3.7	38.5	4.3	4.1	136.3	2.3	5.0	164.9	2.7
30	42.8	3.4	38.5	3.8	4.1	136.4	2.3	5.0	164.9	2.7
31	43.1	4.0	38.8	4.2	4.2	138.9	2.3	5.0	164.9	2.7
32	43.6	4.0	38.9	3.6	4.2	137.0	2.3	5.0	164.9	2.7
33	43.4	3.3	39.3	4.2	4.2	138.1	2.3	5.0	164.9	2.7
34	43.3	3.5	39.3	4.1	4.2	138.9	2.3	5.0	164.9	2.7
35	43.7	3.1	39.4	4.0	4.1	134.7	2.2	5.0	164.9	2.7
36	43.6	3.6	39.7	4.3	4.1	136.6	2.3	5.0	164.9	2.7
37	43.7	3.1	39.6	4.2	4.1	135.0	2.3	4.9	160.3	2.7
38	43.8	3.0	39.9	4.4	4.1	134.2	2.2	5.0	164.9	2.7
39	43.9	2.8	39.7	3.9	4.0	133.5	2.2	5.0	164.9	2.7
40	43.8	3.2	40.1	4.5	4.1	134.6	2.2	4.9	162.4	2.7
41	44.2	3.5	40.1	3.9	4.1	136.4	2.3	5.0	164.9	2.7
42	44.1	3.1	40.1	4.3	4.1	134.1	2.2	5.0	164.9	2.7

43	44.5	3.5	40.5	4.2	4.1	135.2	2.3	5.0	164.9	2.7
44	44.5	3.5	40.2	3.8	4.0	131.5	2.2	5.0	164.9	2.7
45	44.3	3.1	40.4	3.8	4.1	133.7	2.2	5.0	164.9	2.7
46	43.9	3.2	40.4	4.0	4.0	132.9	2.2	5.0	164.9	2.7
47	44.6	3.4	40.6	4.1	4.1	135.5	2.3	5.0	164.9	2.7
48	44.6	3.4	40.4	4.3	4.0	133.0	2.2	4.9	162.9	2.7
49	44.6	3.7	40.5	4.1	4.0	133.3	2.2	5.0	164.9	2.7
50	44.6	3.7	40.6	4.3	4.0	132.6	2.2	5.0	164.9	2.7
51	44.7	3.3	40.3	4.2	4.0	133.3	2.2	5.0	164.9	2.7
52	44.6	3.3	40.7	4.5	4.0	132.3	2.2	5.0	164.9	2.7
53	44.5	3.0	40.5	4.3	4.0	133.3	2.2	5.0	164.9	2.7
54	44.6	3.3	40.5	4.3	4.1	134.3	2.2	5.0	164.9	2.7
55	44.6	3.0	40.8	4.0	3.9	130.9	2.2	5.0	164.9	2.7
56	45.0	3.3	40.4	3.5	4.0	133.2	2.2	5.0	164.9	2.7
57	44.7	3.5	40.7	3.9	3.9	129.6	2.2	5.0	164.9	2.7
58	44.7	3.1	40.5	4.2	4.0	131.6	2.2	5.0	164.9	2.7
59	44.6	3.1	40.7	4.2	4.1	133.7	2.2	5.0	164.9	2.7
60	44.7	3.5	40.8	4.4	4.0	133.4	2.2	4.9	161.2	2.7

Geiger-Mueller Tube Technical Data

BACKGROUND

Simple Geiger-Mueller tubes similar to type used in the LGI are referred to as mica end window tubes. The stainless steel tube is hermetically capped with a thin sheet of mica only .001 to .002 grams in mass. The interior of the sealed tube has an anode rod running the length of the long axis of the tube, and the tube contains neon gas spiked with a halogen contaminant. When an incoming alpha, beta or gamma causes a neon atom to lose an electron, the ejected electron finds itself pushed very strongly toward the anode rod while the neon ion is pushed strongly toward the steel case of the tube. Along the way, collisions with these charged particles cause other neon atoms to lose their electrons. From a singular disintegration, an avalanche builds in a few microseconds, as momentary conduction through the neon gas occurs, driven by the 450 to 500 volt potential between anode rod and case. As neon ions acquire electrons from the case, the neon atoms return to an excited metastable state. This means that the neon atoms, although now neutral, still have energy to give up before they return to their ground state. This energy would keep the tube continuously discharging. The halogen gas contaminant is designed to "quench" this continuous discharge by absorbing the energy released by the neon as it falls from its neutral metastable excited state to the ground state. Typically, it takes 100 microseconds for the avalanche of neon ions to be neutralized to their ground state.

TYPICAL GEIGER-MUELLER TUBE CHARACTERISTICS

1.	Sensitivity	alpha, beta, gamma
2.	Window thickness	1 to 2 mg/sq. cm.
3.	Gas filling	Neon + Halogen
4.	Starting voltage	400 V DC
5.	Operating voltage	450 V DC to 550 V DC
6.	Dead time	100 microseconds
7.	Background from unit	10 counts per minute max.
8.	Capacitance	4 picofarads
9.	Operating temp. range	-40 to +75 degrees C.
10.	Tube life	10 billion counts

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Certificate of Analysis

Titanium foil, 0.25mm (0.0098in) thick, 99.99+%
(metals basis)

Stock Number: 13975
Lot Number: G07D10

ANALYSIS

Li	<0.004	Be	<0.002	B	<0.004	Na	<0.035	Mg	<0.010
Al	2.350	Si	0.430	P	<0.006	K	<0.030	Ti	Martix
V	0.910	Cr	1.150	Mn	<0.026	Fe	6.600	Co	0.048
Ni	0.060	Zn	<0.035	Ga	<0.015	Ge	<0.025	As	<0.015
Se	<0.050	Br	<0.050	Zr	1.200	Ru	<0.009	Rh	0.300
Pd	<0.009	Ag	<0.015	Cd	<0.085	In	<0.009	Sn	0.300
Sb	<0.030	Te	<0.075	I	<0.040	Cs	<0.002	Ba	<0.0010
La	<0.0008	Ce	<0.0010	Nd	<0.004	Hf	0.025	W	<0.224
Re	<0.003	Os	<0.006	Ir	<0.006	Pt	<0.015	Au	<0.070
Hg	<0.010	Tl	<0.010	Pb	<0.008	Bi	<0.005	Th	<0.0004
U	<0.0004	S	4.000*	H	2.0*	C	24.5*	B	17.0*
O	250.0*								

Ion Interference:

Ca	<0.450	Sc	<0.050	Cu	1.850	Rb	<3.0	Sr	<2450.0
Y	<210.0	Nb	<0.400	Mo	<0.065				

Instrument Contamination:

F	<0.950	Cl	<1.000	Ta	<6.500

* LECO; All others by GDMS   Analysis is in ppm

Certified By:

Michael Early
Product Specialist

JM
Johnson Matthey
JOHNSON MATTHEY CATALOG COMPANY